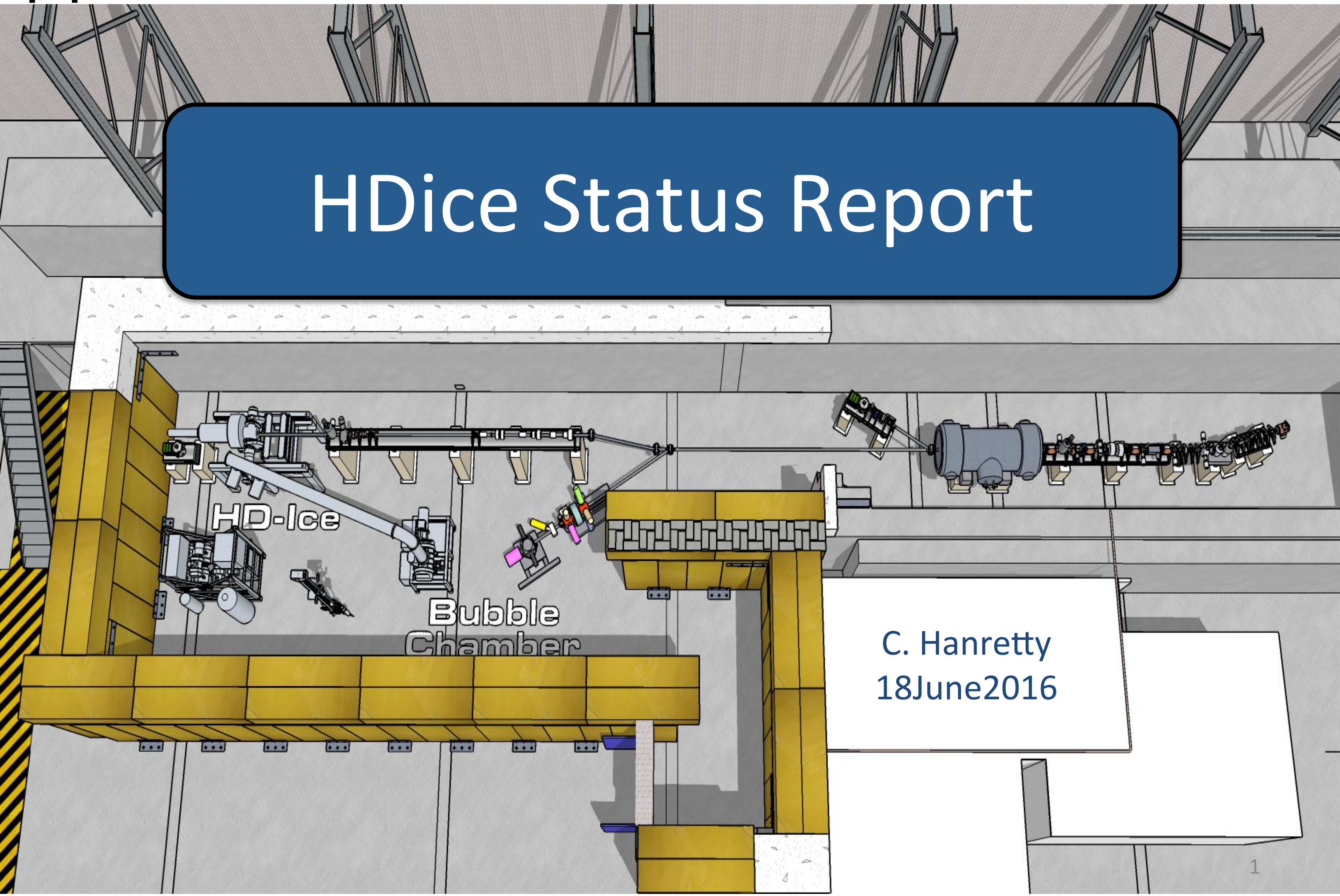
HDice Status Report



C. Hanretty
18June2016

Collaborators

Jefferson Lab (HDice – Physics Div)
G. Dezern, C. Hanretty, T. Kageya, M. Lowry, A. M. Sandorfi, X. Wei

Jefferson Lab (UITF – Accelerator Div)
H. Areti, J. Grames, J. Gubeli, M. Poelker, W. Akers

Universita di Roma Tor Vergata and INFN-Sezione di Roma2 (Gas analysis)
A. D'Angelo

James Madison University (Gas distillation)
C.S. Whisnant

Universita di Ferrara and INFN di Ferrara (MgB_2 magnet)
M. Contalbrigo, P. Lenisa, M. Statera, G. Ciullo, L. Barion

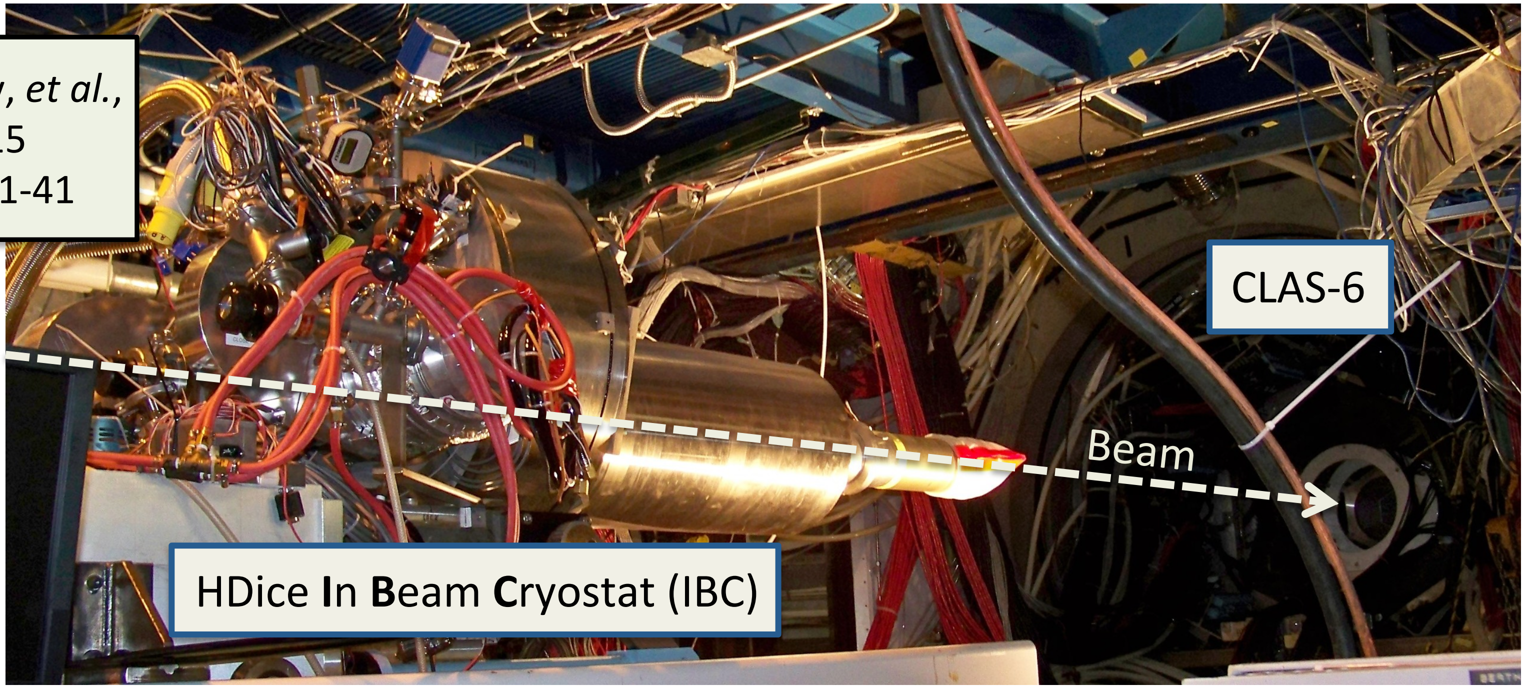
Overview

- Depolarization mechanisms from a charged beam: 2012 eHD tests in Hall B
- eHD at the Upgraded Injector Test Facility (UITF)
- Relating running at eHD at UITF to running in CLAS-12
- Achieving transverse polarization inside CLAS-12 Solenoid with a perfect diamagnet (MgB_2)

What is HDice?

- A frozen spin target ⟶ no need for large magnet.
- Target material consists solely of polarizable protons and deuterons ⟶ no dilution factor coming from the target material.
- Target material possesses a T1 (relaxation time) on the order of years.
- A very complicated target system requiring many steps in the production of a single polarized target cell.

M. Lowry, *et al.*, NIM A 815 (2016), 31-41



What experiments benefit?

- Has been used with photons in Hall B as part of the N* program → g14 (Nov 2011 – May 2012).
- Next up: Transversely polarized frozen spin target for use with electrons.
- Three (A-rated) proposals approved by PAC 39, rated as high impact for Hall B by PAC41:
  - SIDIS, C12-11-111, Marco Contalbrigo,… [A;C1]
  - Dihadron production, PR-12-009, Harut Avakian,… [A;C1]
  - DVCS, PR12-12-101, Latifa Elouadrhiri,… [A;C1]

HDice

Jefferson Lab

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  - DVCS, PR12-12-101, Latifa Elouadrhiri,… [A;**C1**]

C1 → scheduling requires successful demonstration of viable performance in a subsequent eHD test runs

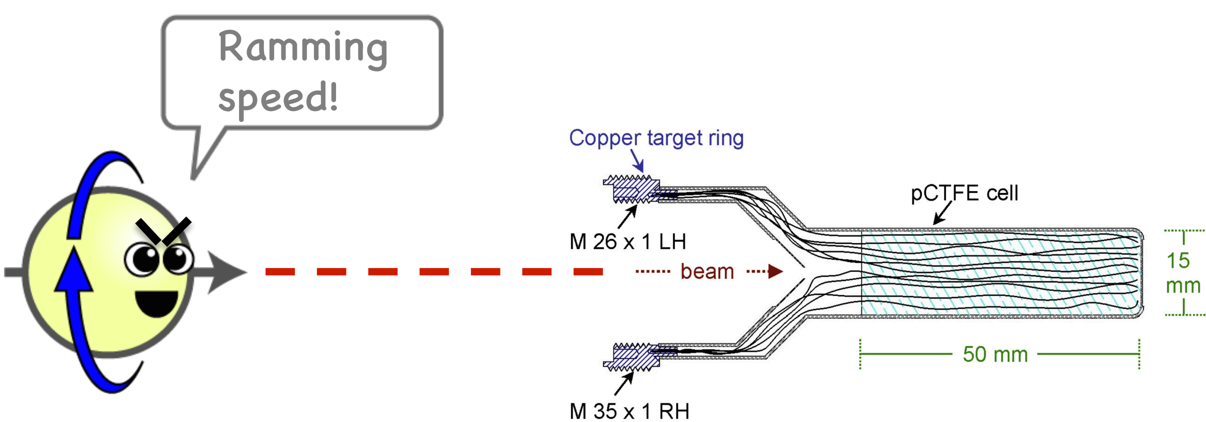
Why use HDice?

- These proposals require transversely polarized target.
- A conventional target with transverse polarization requires use of “large” magnet around target (DNP)
  - A magnetic field transverse to beam axis bends beam into detectors (sheet of flame).
  - Frozen spin target does not require large magnetic field around target (smaller B • dl) ⇒ HDice

- Maintaining a transverse field inside of CLAS-12 Solenoid can be possible using MgB_2 cylinder inside of IBC.

2012 eHD Test in Hall B

- During g14, several eHD runs were conducted opportunistically to study the effect of an electron beam on the HDice target.
- eHD test utilized existing Hall B Slow-Raster and target cell designed for photons (a setup not optimized for an electron beam).
- Results showed a significant loss of polarization due to the electron beam (1/e ≈ 1/2 nA-day) ⇒ Focus of current R&D effort



2012 eHD Test in Hall B

- Depolarization attributed to three possible mechanisms:

1) Beam-induced chemical changes
   - HD molecule ionizes and becomes highly reactive (HD^+)
   - A chain of reactions begins, producing atomic hydrogen:
     ➔ Temperature spikes occur from "recombination flashes"
       - Also seen in g14 photon runs (from $e^+ e^-$ pairs) with low frequently but with no apparent effect.

     ➔ Possible buildup of ortho-H_2 which could shorten T1 of material
       - Analysis of gas after 1nA-week in beam showed no large increase of ortho-H_2 (measurements had limited sensitivity)

2012 eHD Test in Hall B

- Depolarization attributed to three possible mechanisms:

2) Hyperfine mixing of unpaired electrons with H (or D) spins
   - Electrons polarized by holding field possess spins opposite to H
   - Hyperfine mixing dilutes H polarization
   - Depolarization first occurs locally, depolarization spreads
   - Temperature independent (function of B^{-2})

Solution:

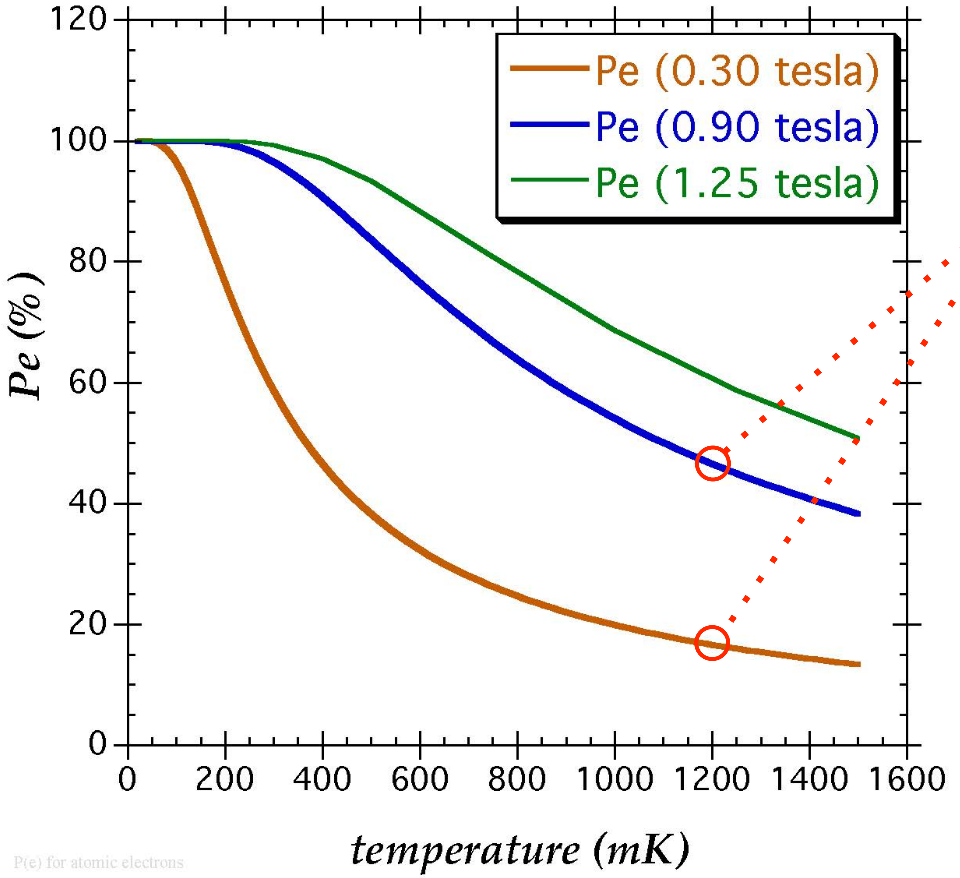
Use RF to align H (or D) spins with electron spins to prevent this mixing.

2012 eHD Test in Hall B

- Depolarization attributed to three possible mechanisms:

3) Beam unpairs 1s molecular electrons in target material
   - Electron(s) may be unpolarized (depends on temperature)
   - If unpolarized (or has low polarization): flips, generating varying field possessing a component at the nuclear Larmor frequencies of H and D
   - Depolarization of local HD begins, spreads to rest of HD crystal

Flipping, unpaired electron during 2012 eHD test



- T(HD) ~ 1.2K in 2012 test runs
  - slow raster
  - too long Alum cooling wires

➔ P_e ~ 20-50%

at $P_e = 0.2$

⇔ e^- population $N_+ = 0.6$, $N_- = 0.4$

and T_1 ~ 4 hr

2012 eHD Test in Hall B

- Depolarization attributed to three possible mechanisms:

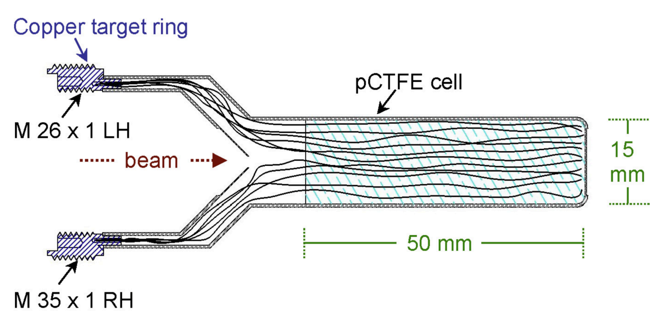
3) Beam unpairs 1s molecular electrons in target material
   - Electron(s) may be unpolarized (depends on temperature)
   - If unpolarized (or has low polarization): flips, generating varying field possessing a component at the nuclear Larmor frequencies of H and D
   - Depolarization of local HD begins, spreads to rest of HD crystal

Solution:

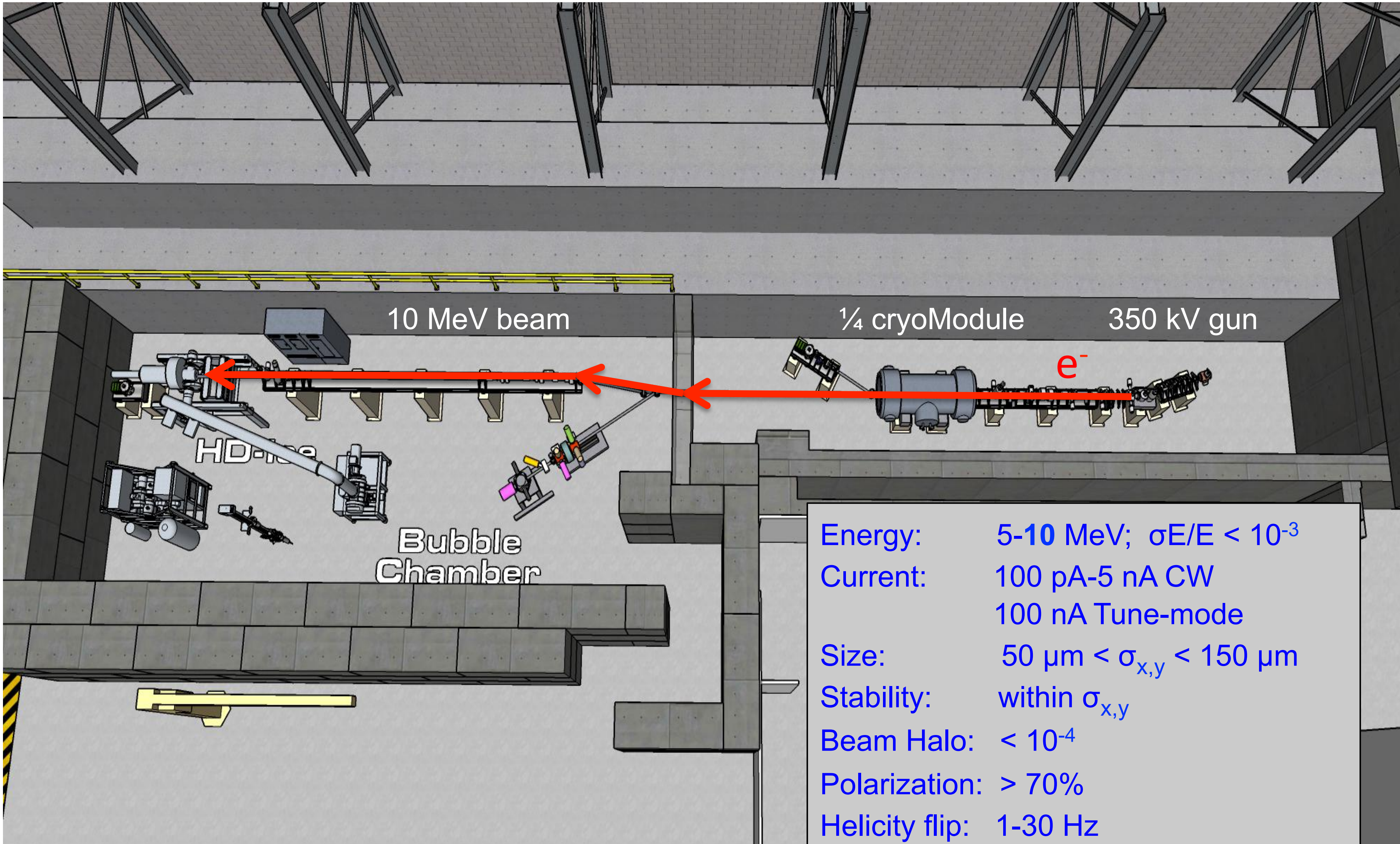
Suppress this effect through higher electron polarization (mitigation of beam heating).

➔ Faster Raster, shorter Al wires, higher purity Al, smaller HD cell

C.D. Bass, *et al.*, NIM A 737 (2014) 107-116

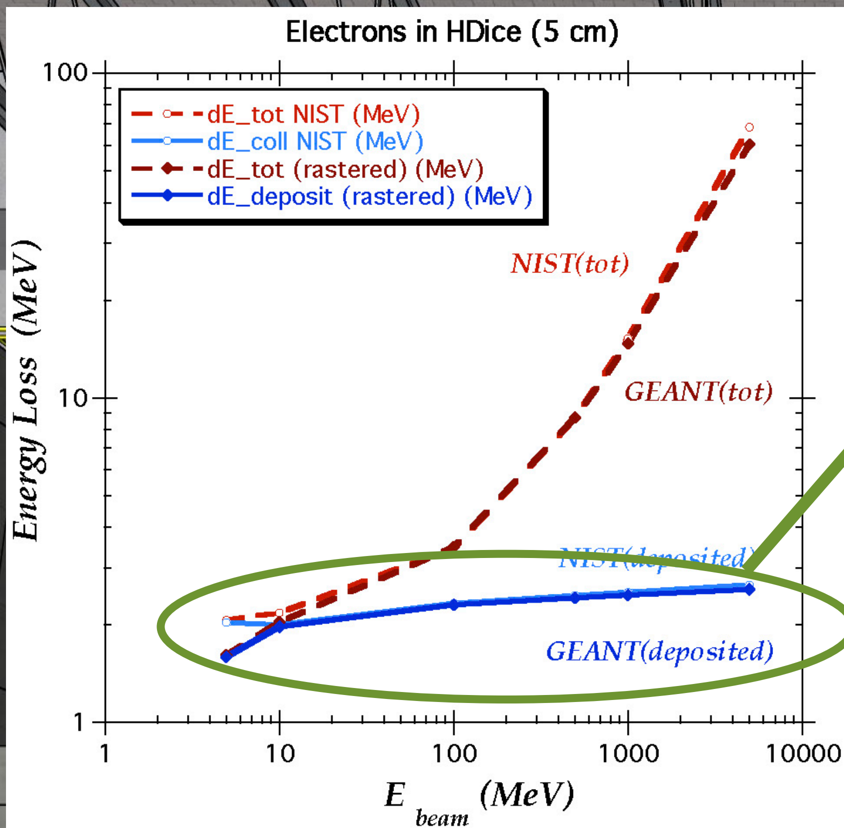


eHD Tests in UITF



Energy:	5-**10** MeV; $\sigma E/E < 10^{-3}$
Current:	100 pA-5 nA CW 100 nA Tune-mode
Size:	50 μm < $\sigma_{x,y}$ < 150 μm
Stability:	within $\sigma_{x,y}$
Beam Halo:	< 10^{-4}
Polarization:	> 70%
Helicity flip:	1-30 Hz

eHD Tests in UITF



Ionization and energy **deposition** are approx independent of E_{beam}

UITF at 10 MeV ≃ Hall B at 10 GeV

Energy:	5-10 MeV; $\sigma E/E < 10^{-3}$
Current:	100 pA-5 nA CW 100 nA Tune-mode
Size:	50 µm < $\sigma_{x,y}$ < 150 µm
Stability:	within $\sigma_{x,y}$
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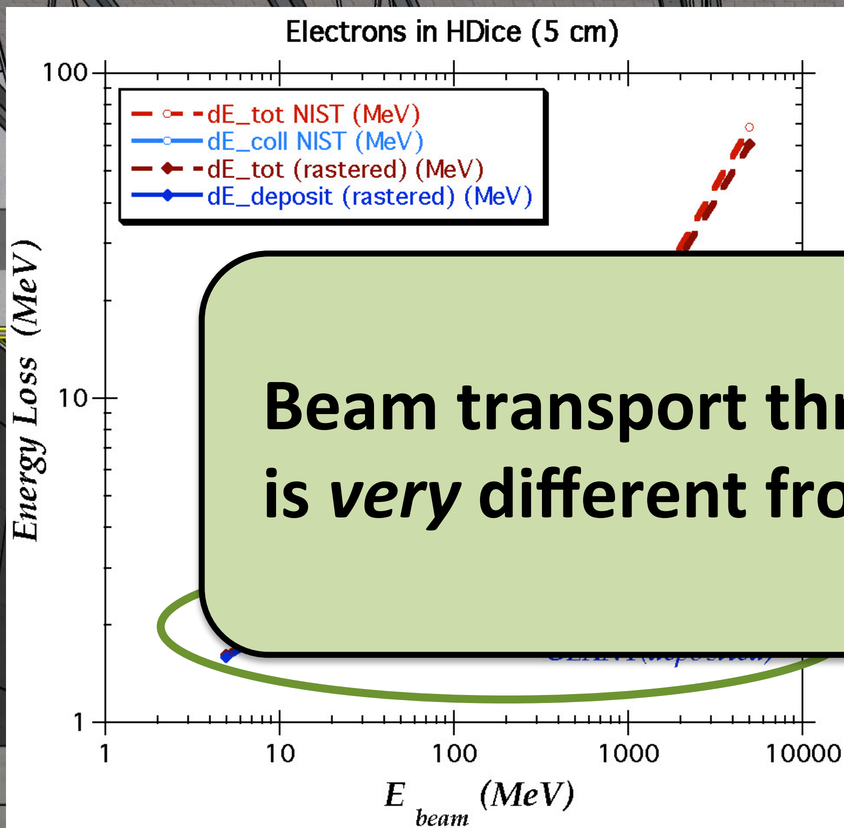
eHD Tests in UITF



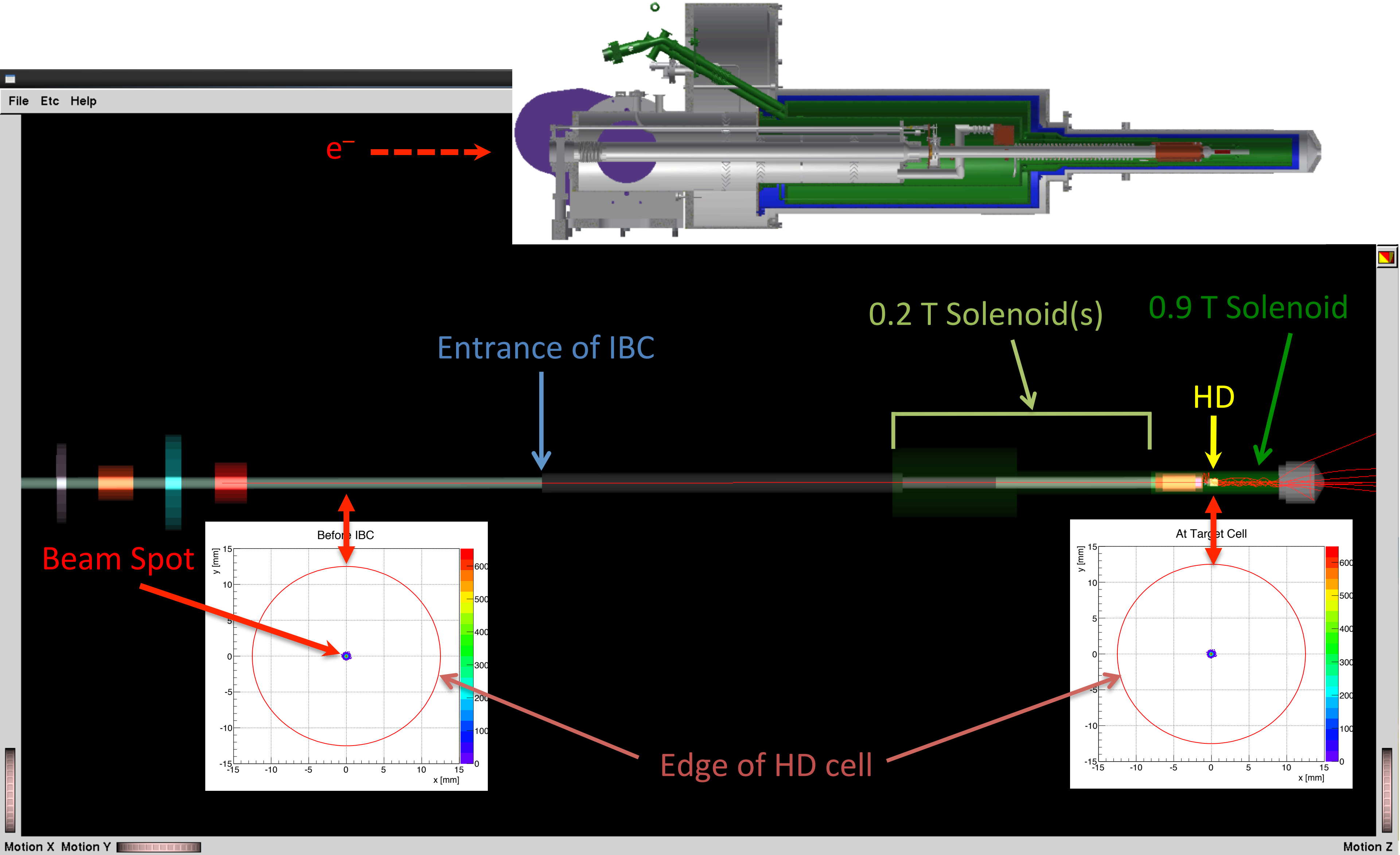
Ionization and energy deposition are approx independent of E_{beam}

at 10 GeV

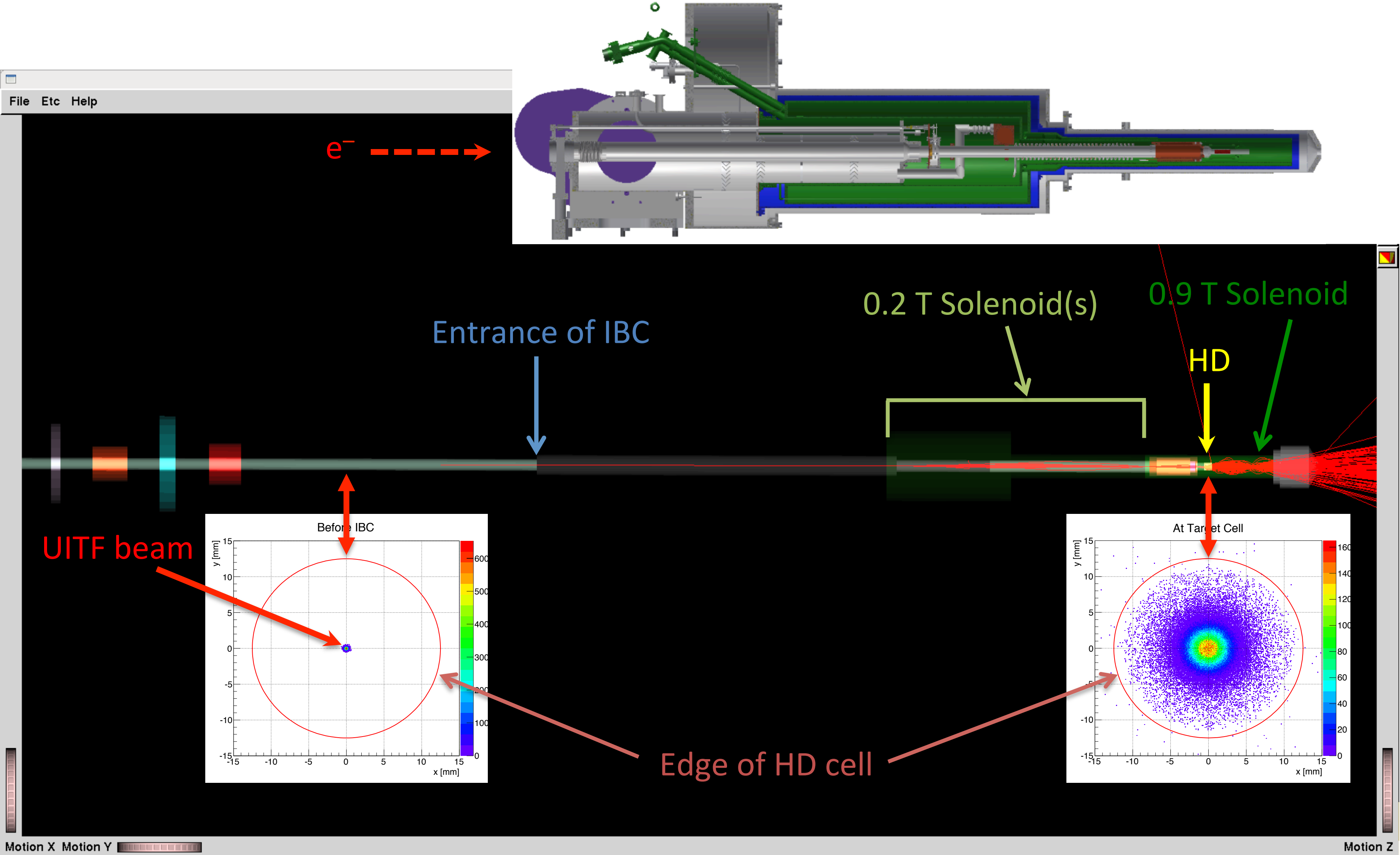
Beam transport through IBC at 10 MeV is *very* different from 10 GeV!!!

Energy:	5-**10** MeV; $\sigma E/E < 10^{-3}$
Current:	100 pA-5 nA CW
	100 nA Tune-mode
Size:	$50\ \mu m < \sigma_{x,y} < 150\ \mu m$
Stability:	within $\sigma_{x,y}$
Beam Halo:	$< 10^{-4}$
Polarization:	> 70%
Helicity flip:	1-30 Hz

Pencil beam into IBC at **10 GeV**

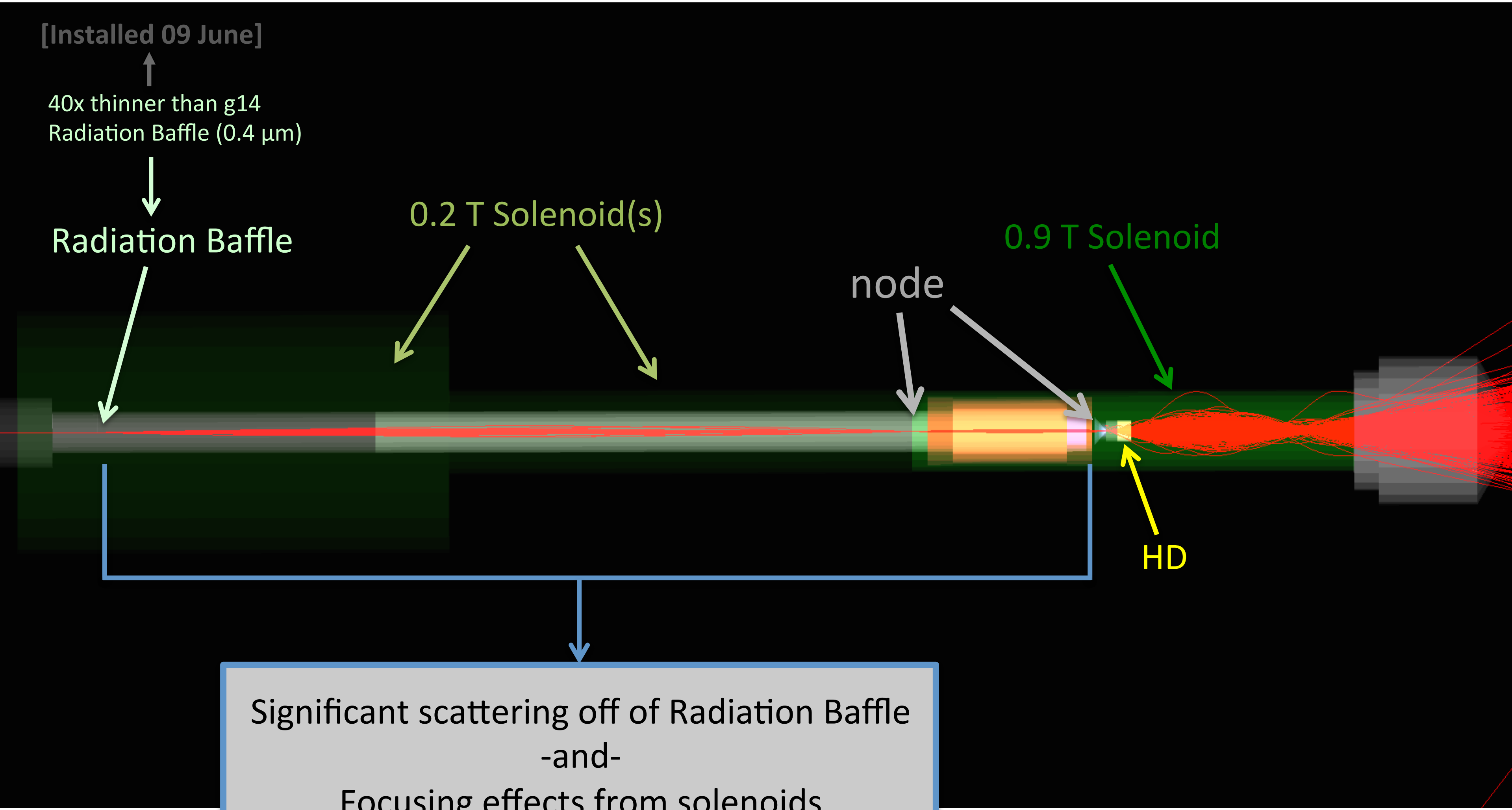


Pencil beam into IBC at **<10 MeV**



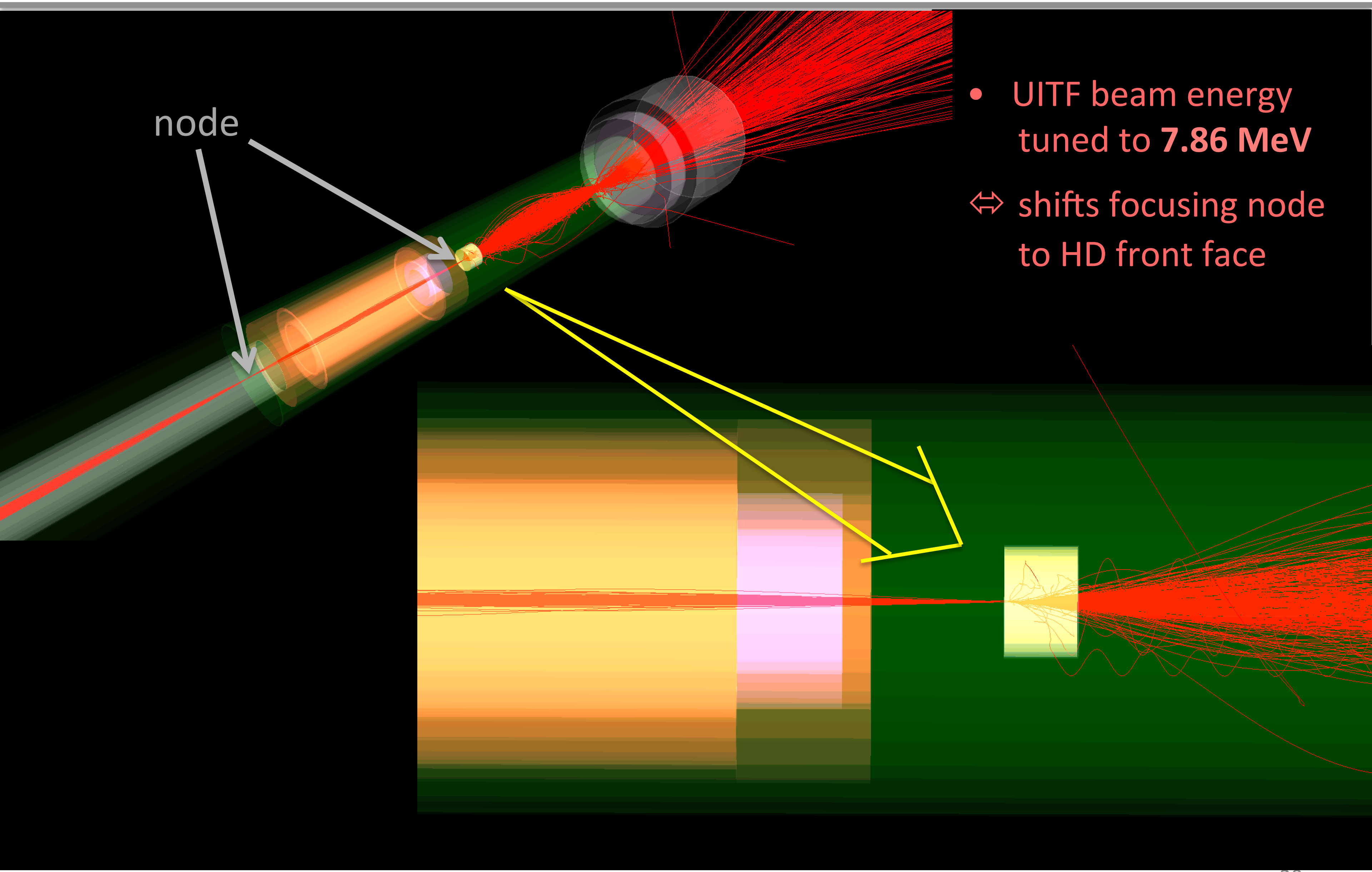
Pencil beam into IBC at **<10 MeV**

…… a closer view



Significant scattering off of Radiation Baffle
-and-
Focusing effects from solenoids

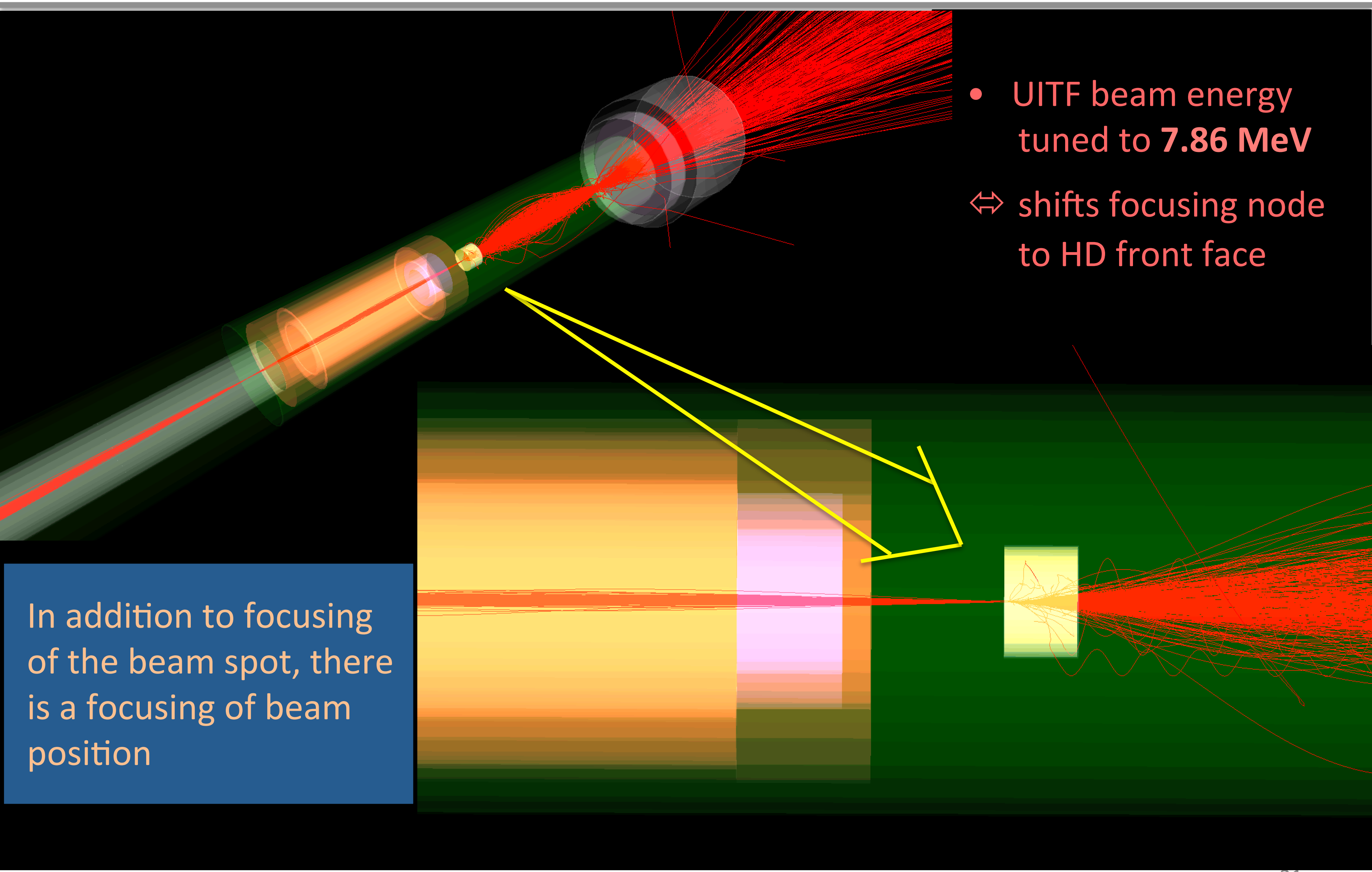
(UITF) Pencil beam into IBC with tuned beam energy



- UITF beam energy tuned to **7.86 MeV**

⇔ shifts focusing node to HD front face

(UITF) Pencil beam into IBC with tuned beam energy



- UITF beam energy tuned to **7.86 MeV**

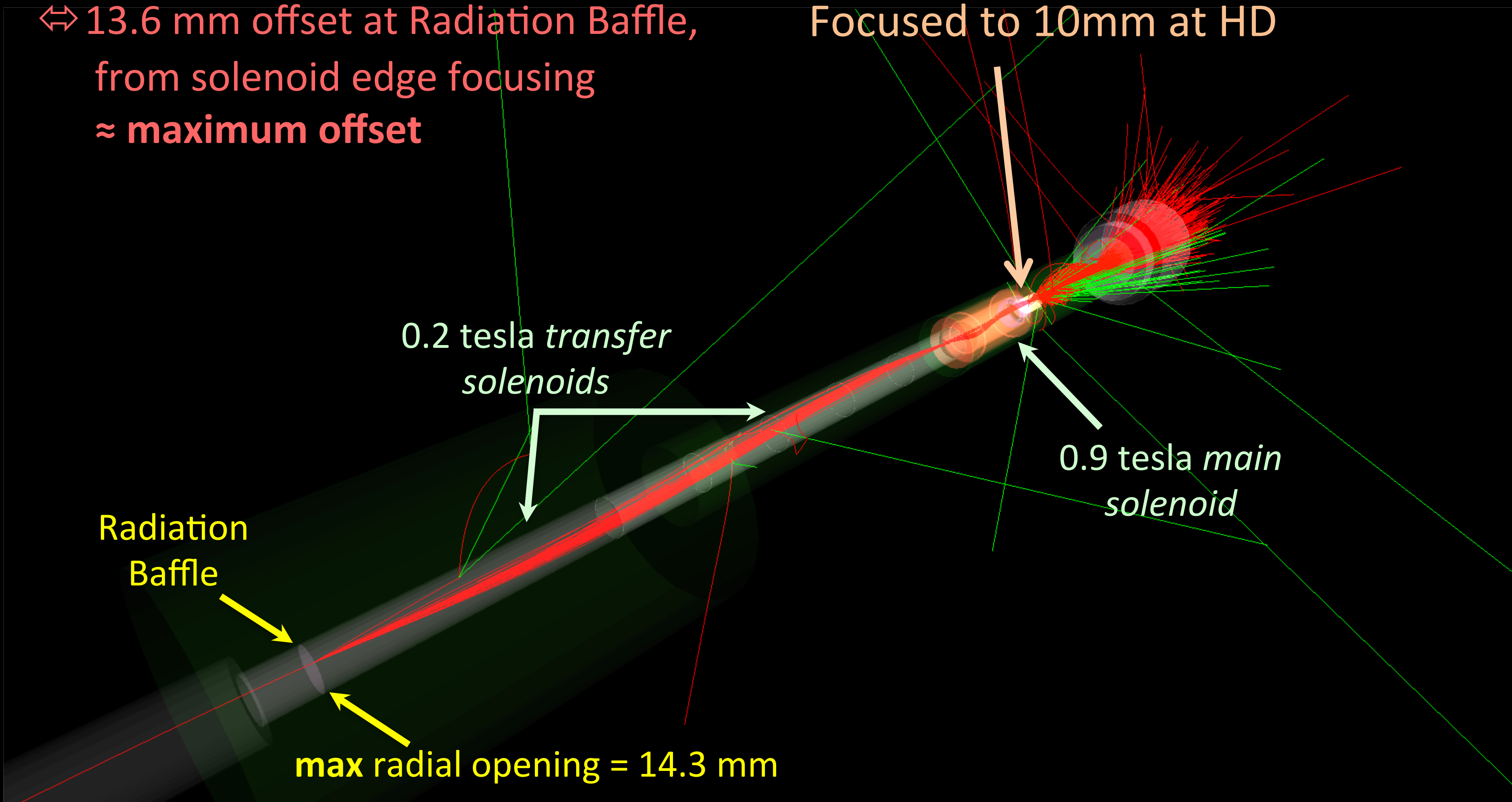
⇔ shifts focusing node to HD front face

In addition to focusing of the beam spot, there is a focusing of beam position

(UITF) Pencil beam into IBC with 14 mm offset

Pencil beam offset 14 mm at launch

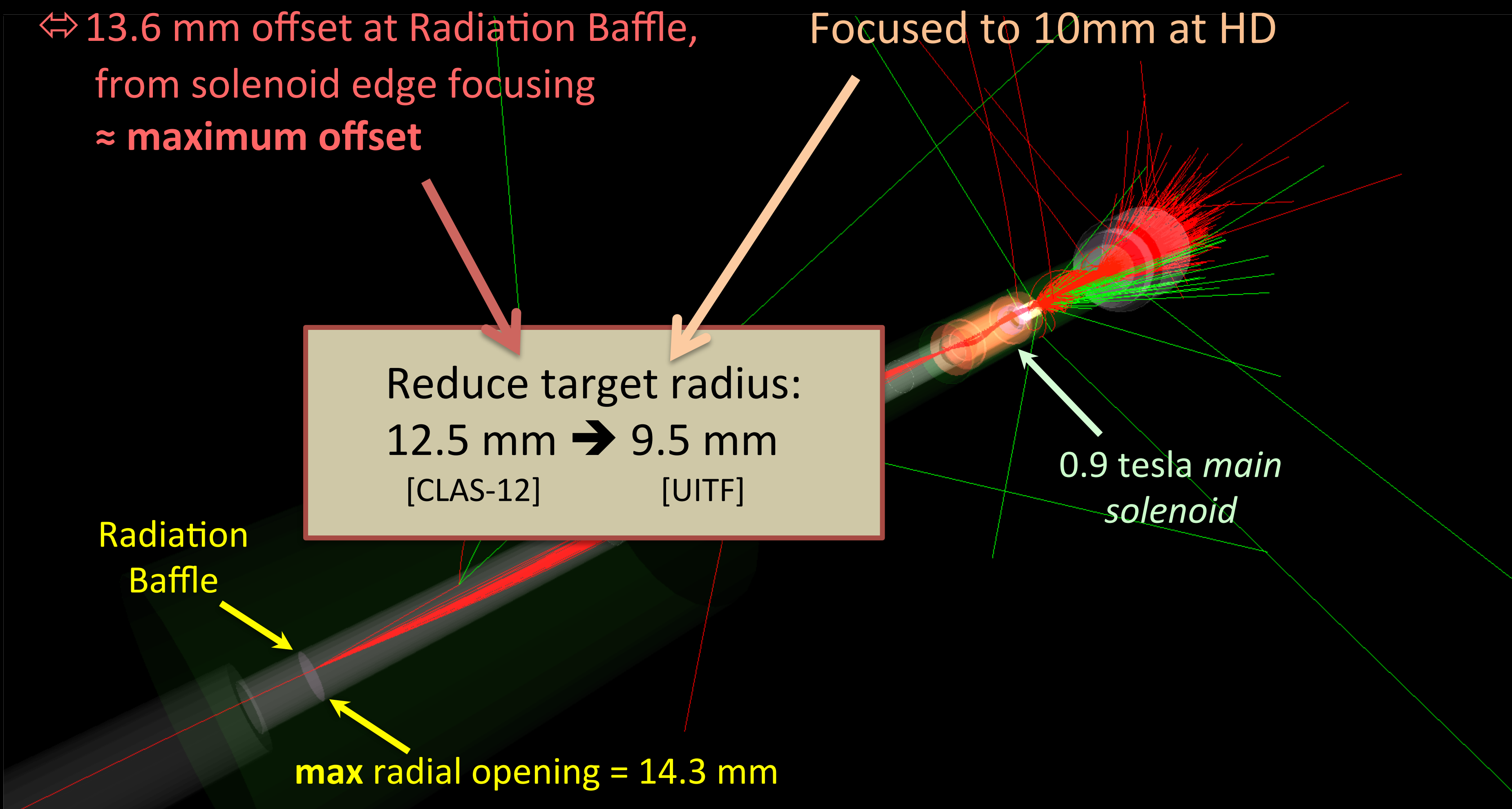
⇔ 13.6 mm offset at Radiation Baffle,
from solenoid edge focusing
≈ maximum offset



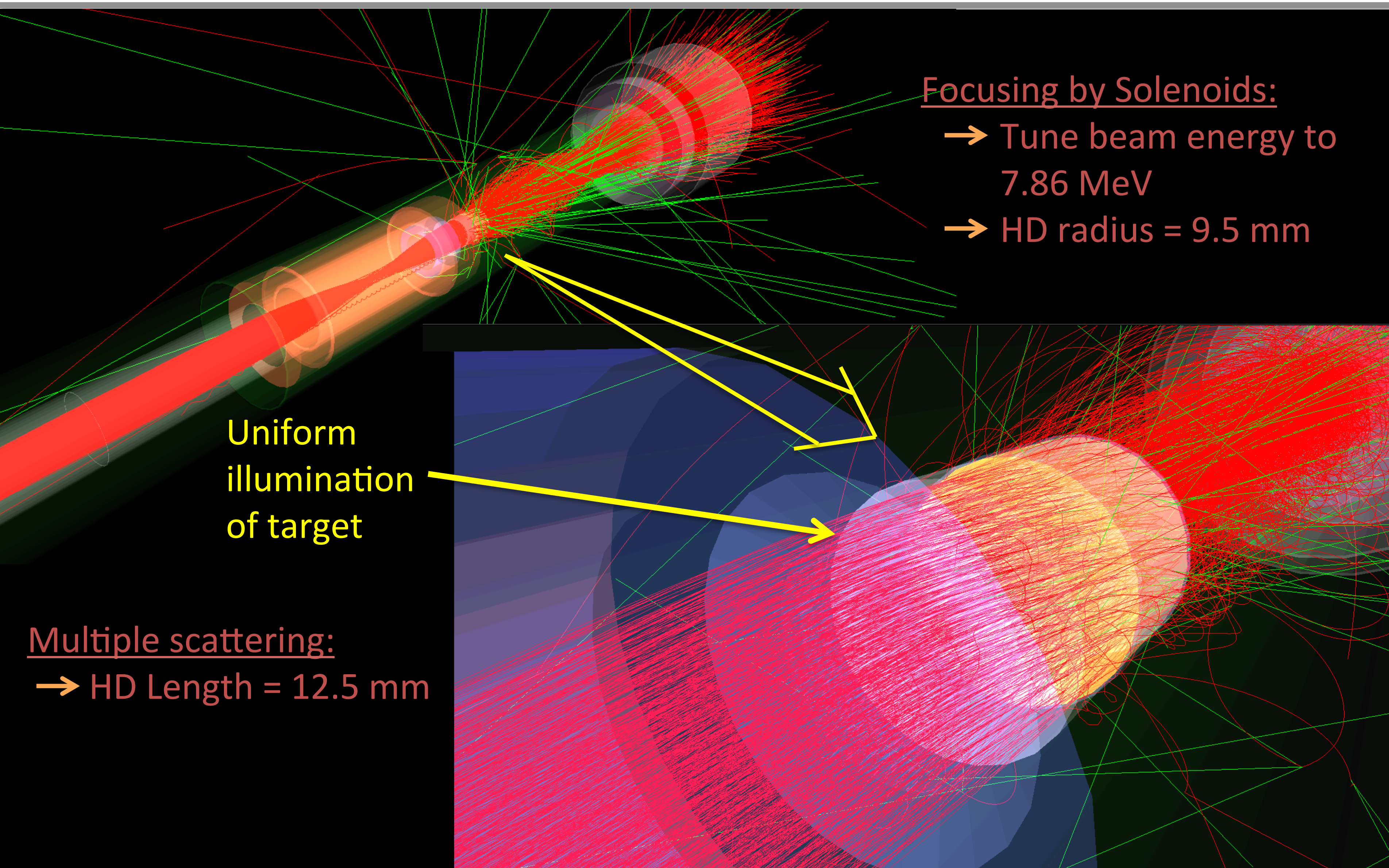
(UITF) Pencil beam into IBC with 14 mm offset

Pencil beam offset 14 mm at launch

⇔ 13.6 mm offset at Radiation Baffle, from solenoid edge focusing **≈ maximum offset**



(UITF) Uniform rastered beam into IBC



Focusing by Solenoids:

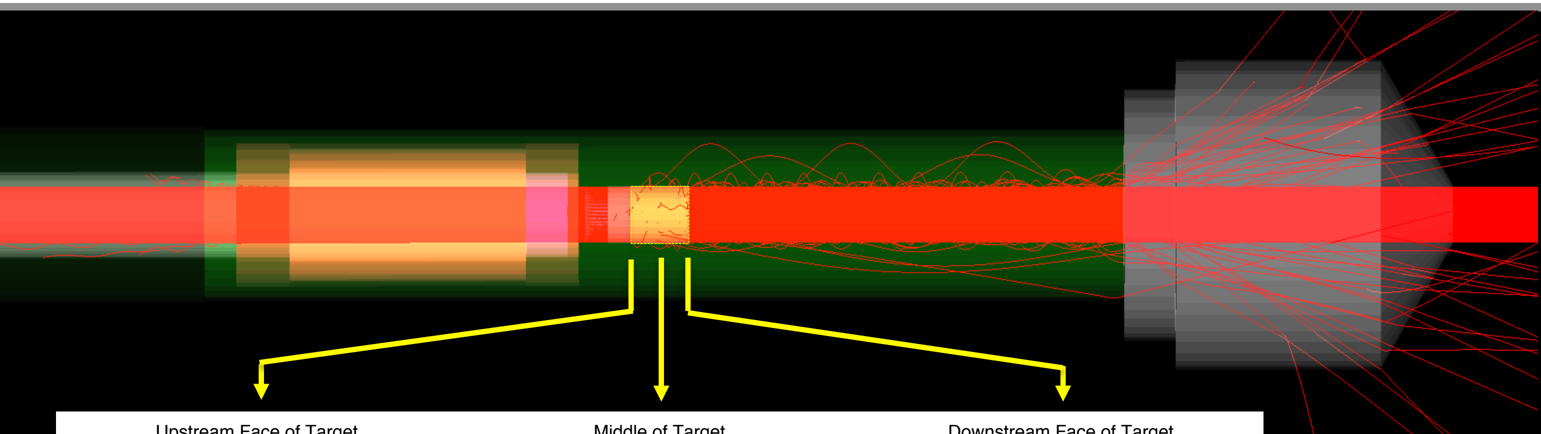
→ Tune beam energy to 7.86 MeV

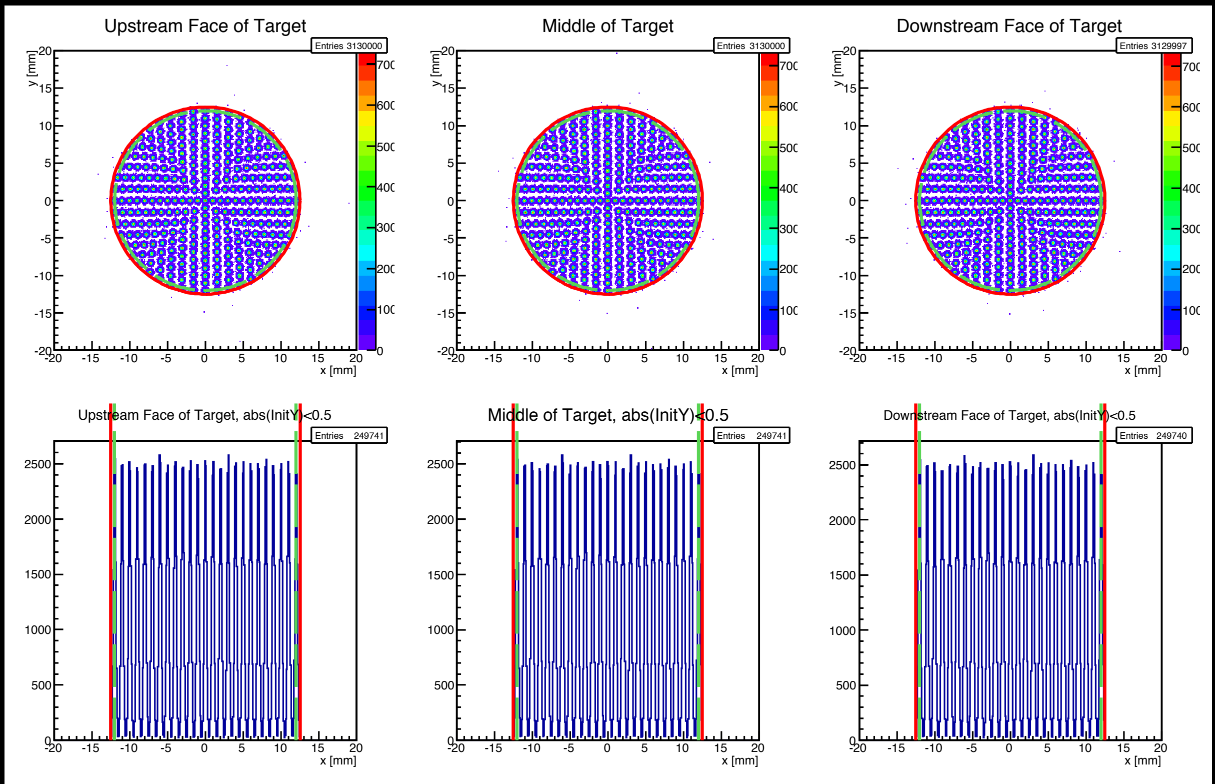
→ HD radius = 9.5 mm

Multiple scattering:

→ HD Length = 12.5 mm

Rastered **10 GeV** beam profiles **CLAS-12** target

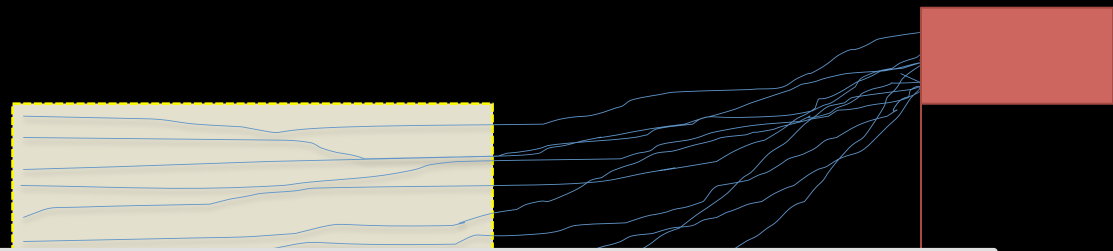




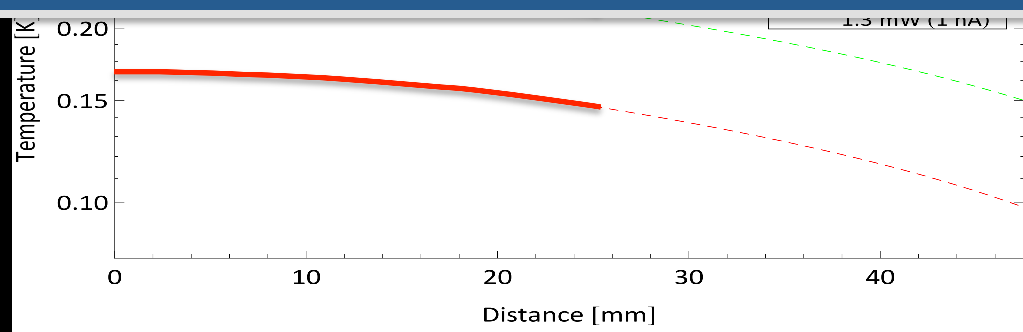
Target radius = 12.5 mm
Target length = 25 mm

- solenoid focusing and multiple scattering are both irrelevant
- beam uniformly illuminates the full target cell

Expected heat load from **10 GeV** on a **CLAS-12** target



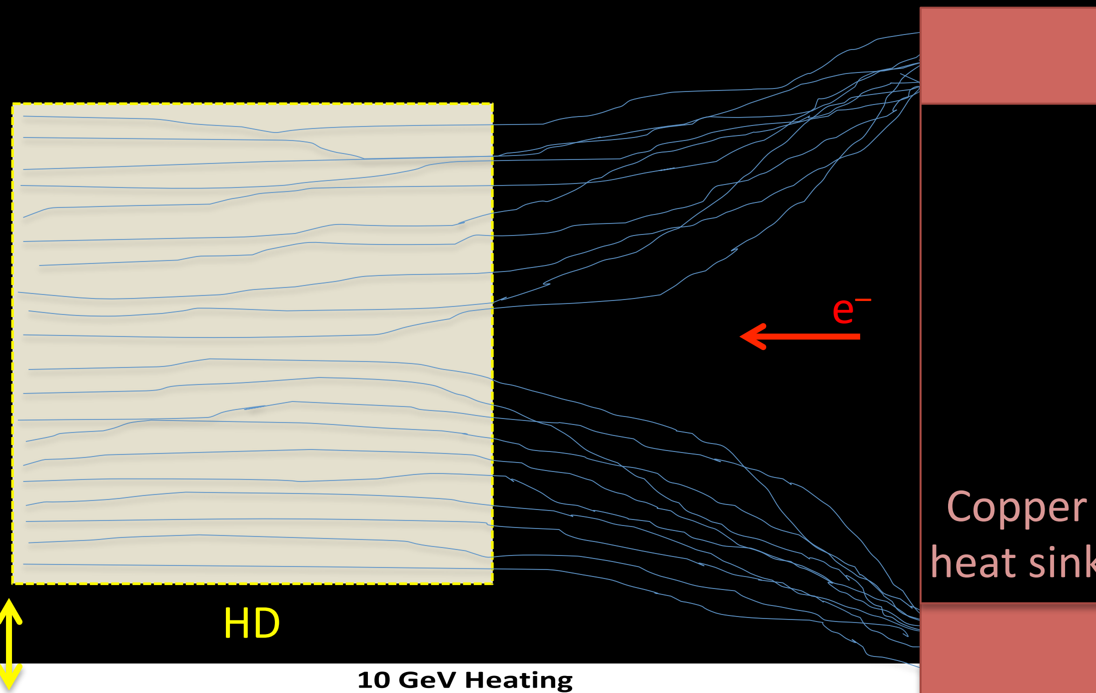
- Depolarization mechanism: beam ionizes HD, breaking paired *1s* electrons
- Unpaired electrons will be inert if they polarize in the 0.9 T IBC field ⇔ **polarization depends on temperature**
- HD temp depends on deposited beam power and temp of Cu heat sink (cooling power of IBC refrigerator)

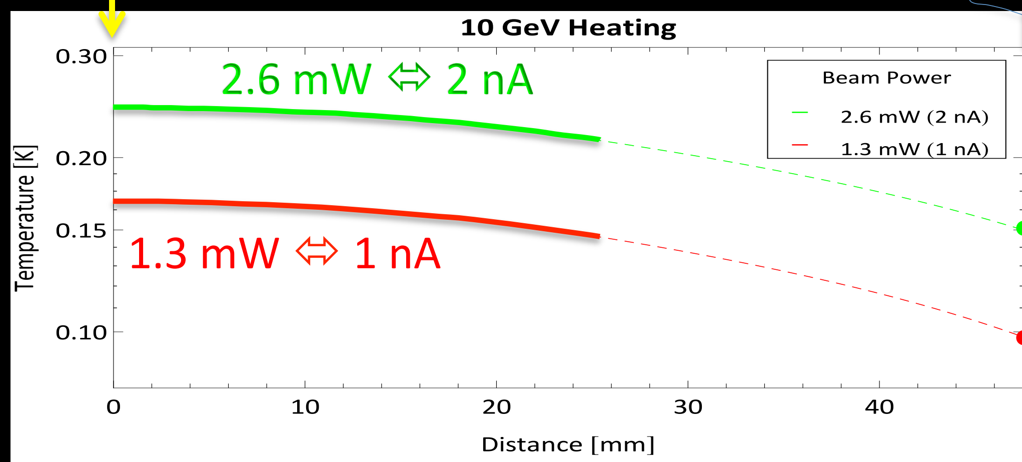


Expected heat load from **10 GeV** on a **CLAS-12** target

- HD cell for CLAS-12:
  25 mm Ø x 25 mm L
  1800 x 3 mil Ø Al (5N) wires
- NEW holding field = 1.25 T

P_e	I_e	Q_{HD}	T_{HD}^{max}
0.99831	2 nA	2.6 mW	245 mK
0.99993	1 nA	1.3 mW	168 mK





T_{cu}

150 mK

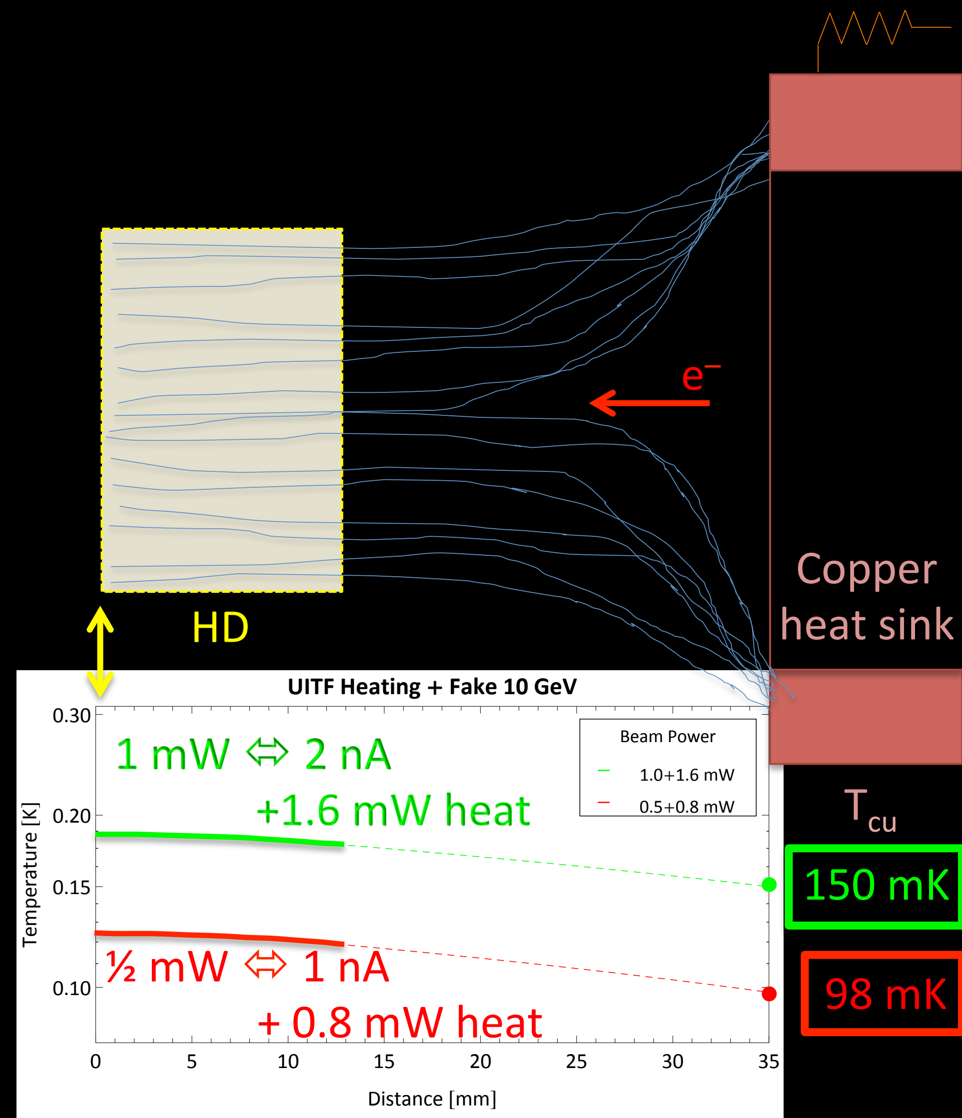
98 mK

Simulating **10 GeV** heat load & polarizations at **UITF**

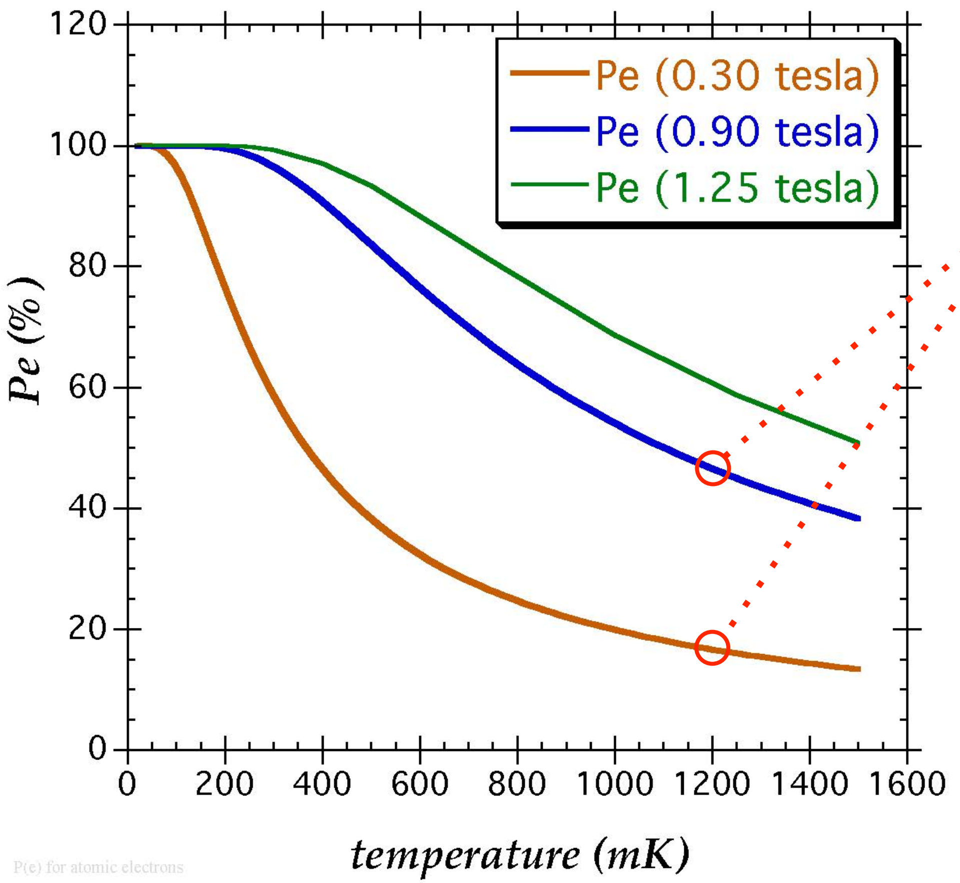
- **UITF** HD cell
- g14 IBC with 0.9 T holding field
- add heat to refrigerator to bring Cu heat sink up to 10 GeV conditions

P_e	I_e	Q_{HD}	T_{HD}^{max}
0.99757	2 nA	1+1.6 mW	186 mK
0.99991	1 nA	½+0.8 mW	125 mK

↑ ~ same P_e as 10 GeV and 1.25 T



For Reference: Flipping, unpaired electron during 2012 eHD test



- T(HD) ~ 1.2K in 2012 test runs
  - slow raster
  - too long Alum cooling wires

➔ P_e ~ 20-50%

at $P_e = 0.2$

⇔ e^- population $N_+ = 0.6$, $N_- = 0.4$

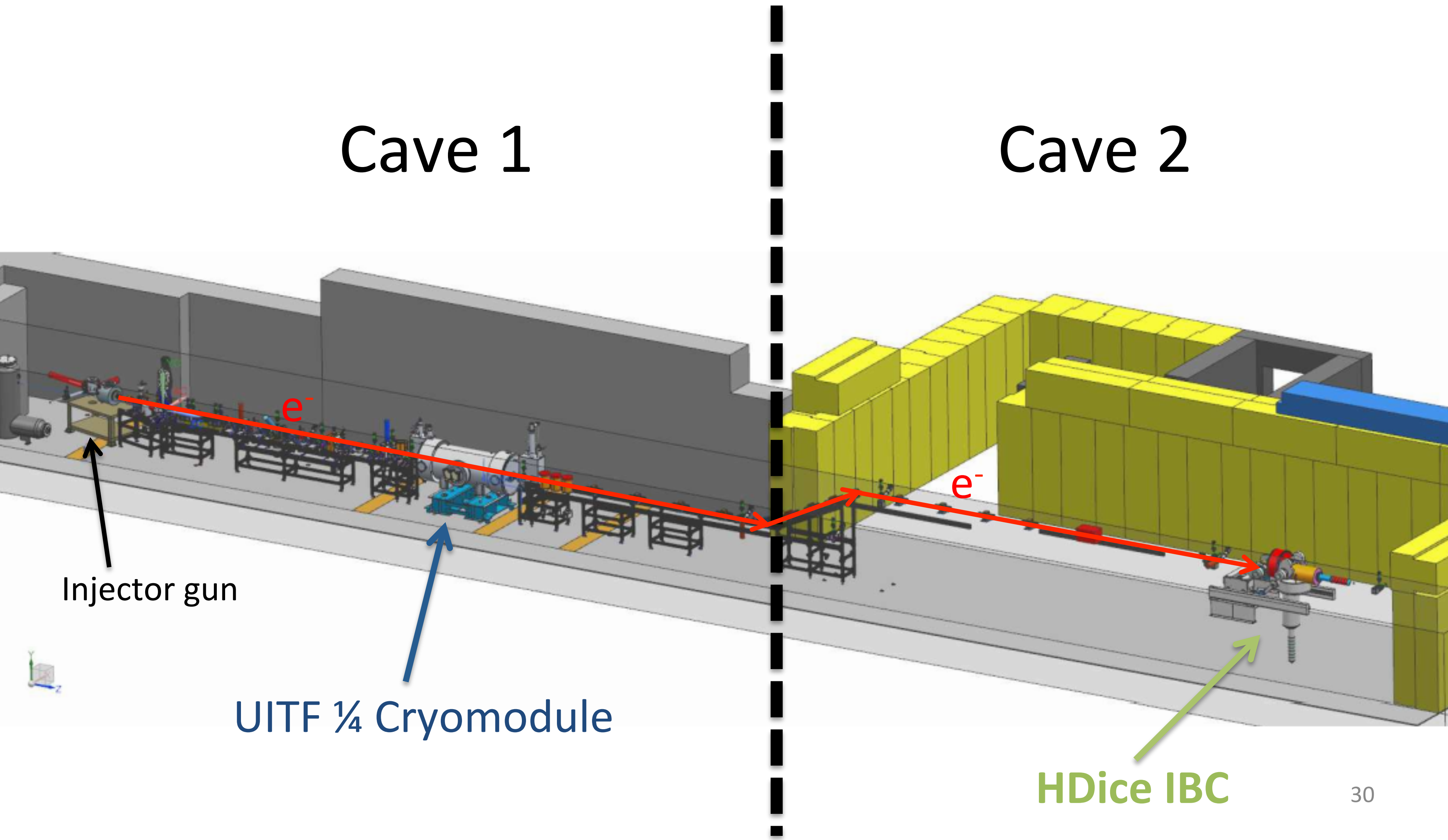
and T_1 ~ 4 hr

➔ at Pe = 0.999

⇔ e- population $N_- = 0.0005$

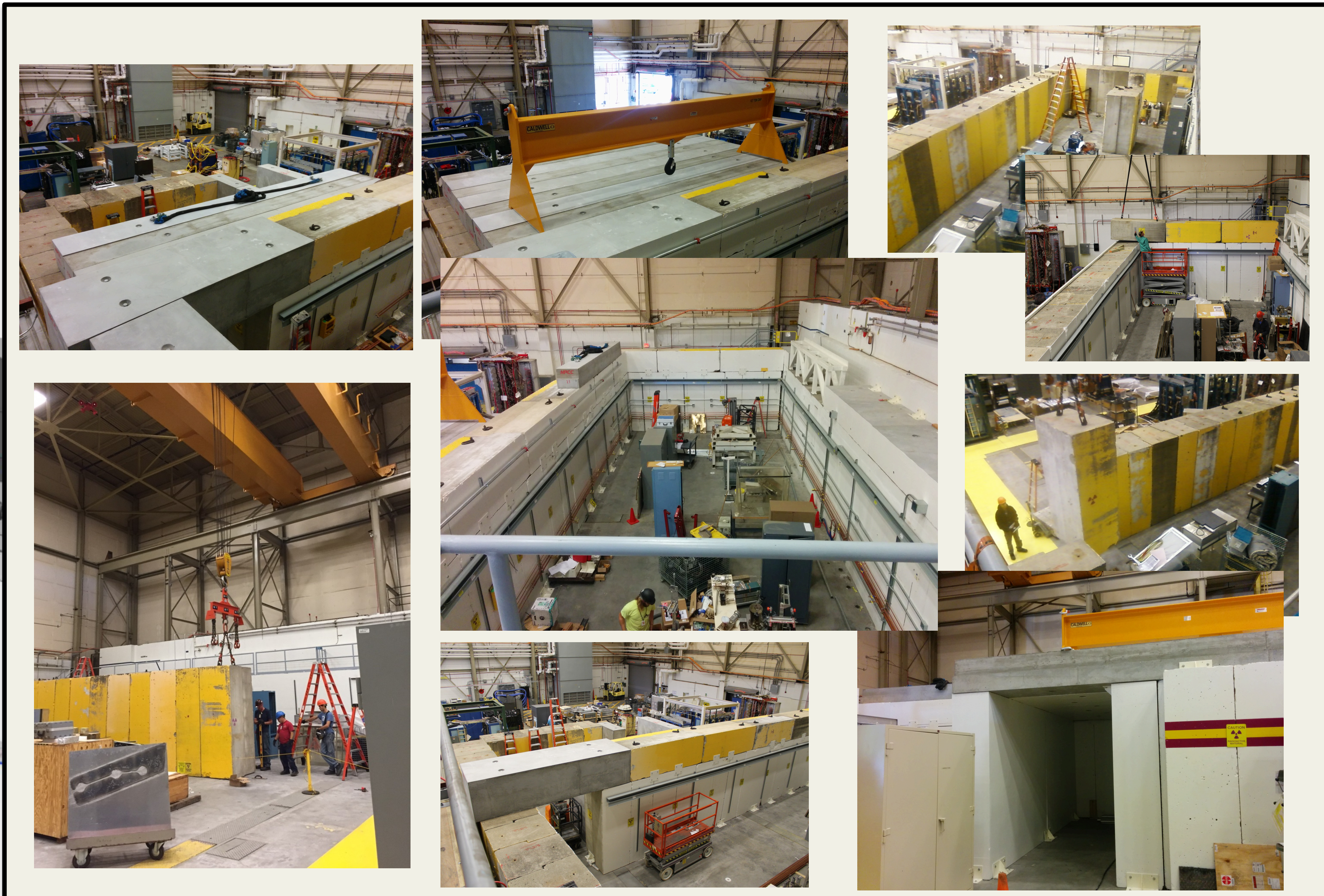
and T_1 should be ~ 4000 hr

Preparing for eHD



Preparing for eHD: Cave 1

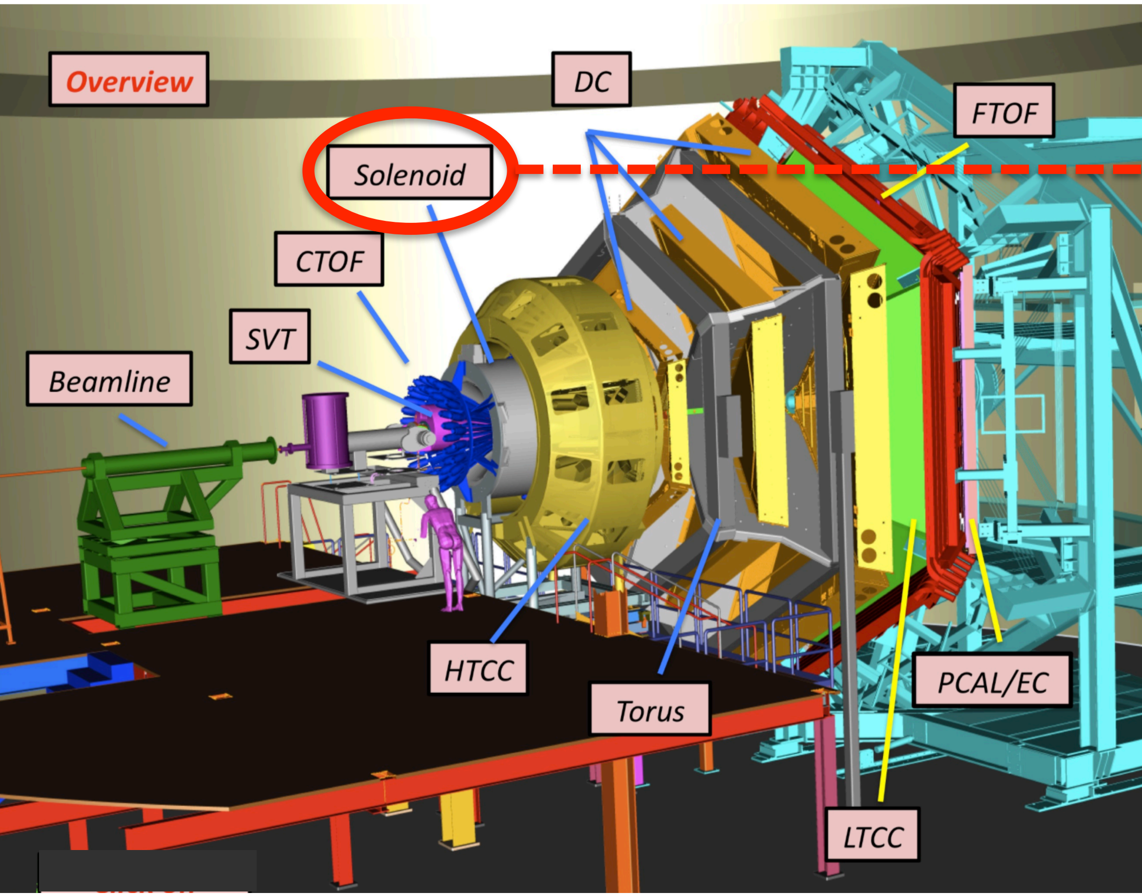
Preparing for eHD: Cave 2

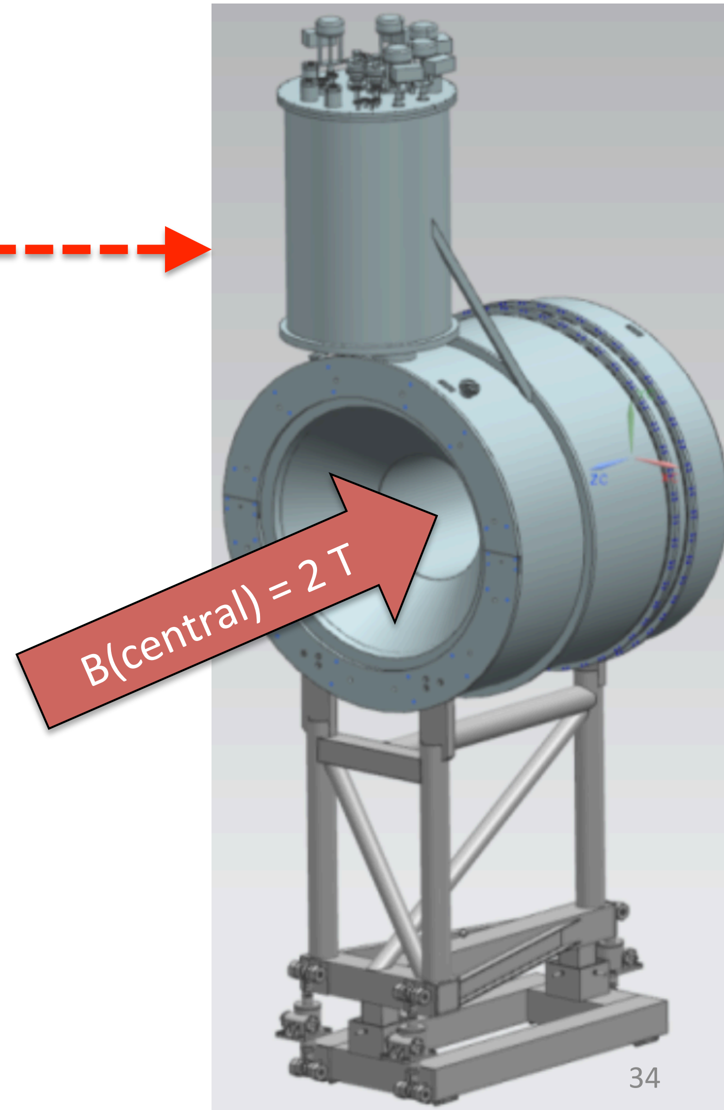


Preparing for eHD: Cave 2

Beam on HDice expected next year!

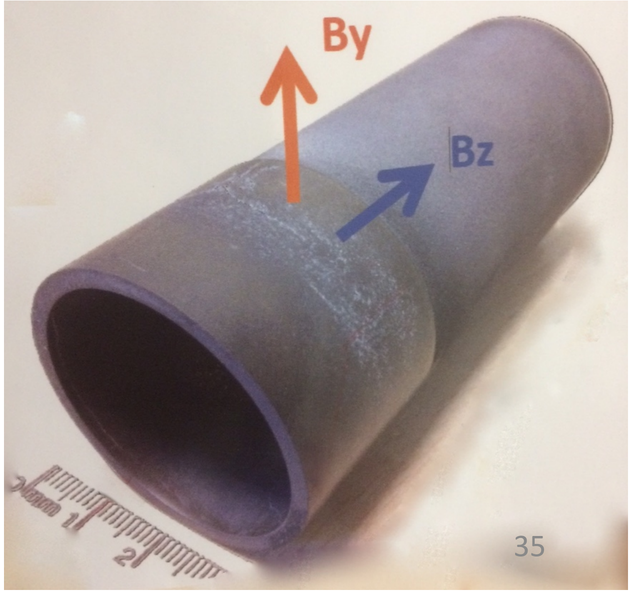
Maintaining a Transverse Holding Field Within the CLAS-12 Solenoid





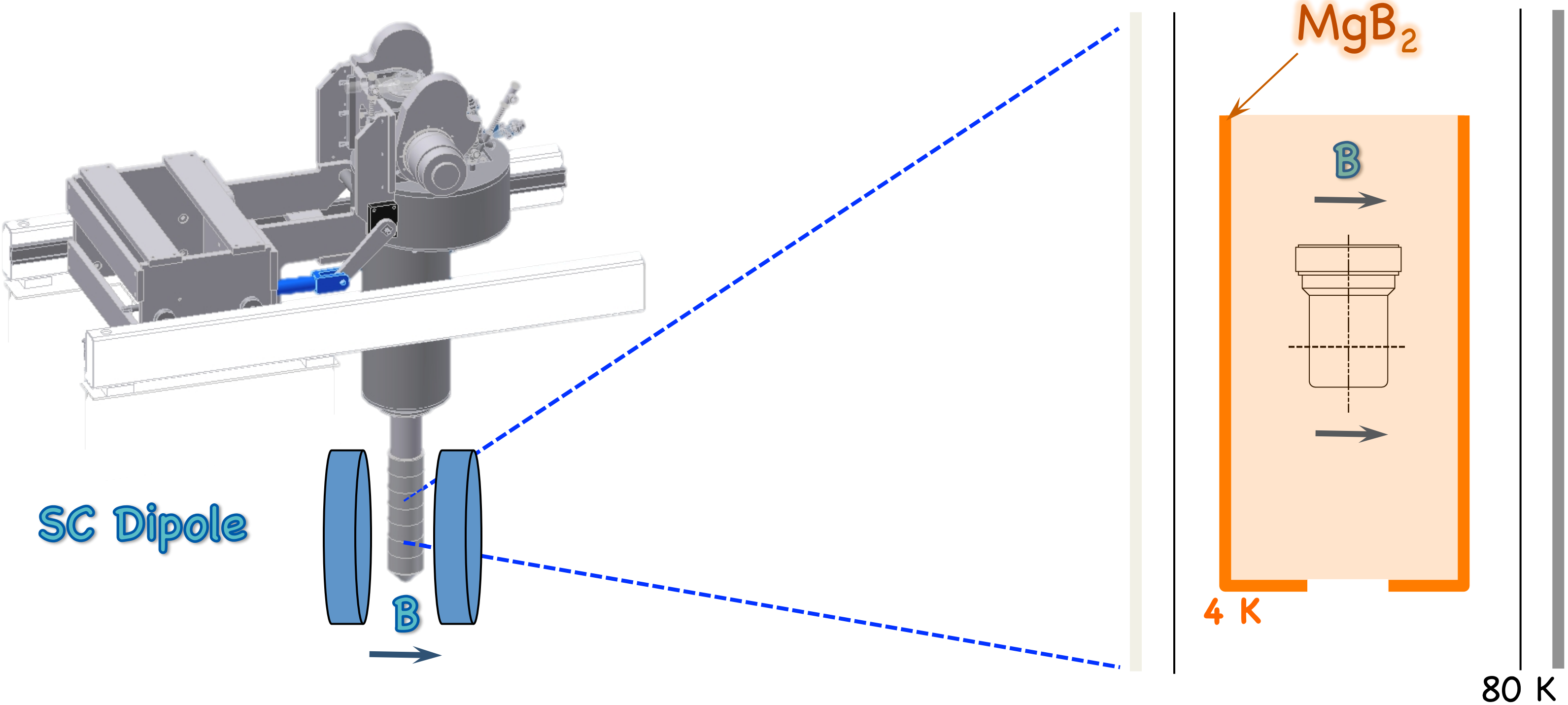
Maintaining a Transverse holding Field within the CLAS-12 Solenoid

- Need to cancel the field of the CLAS-12 Solenoid
- Wound electromagnet:
  - Very difficult to build (uniformity)
  - Must exactly oppose the field of CLAS-12 Solenoid
  - Vulnerable to quenches, other failures (is active device)
  - High <Z>
- Magnesium diBoride (MgB_2)
  - High T_c, superconducting material
  - Can be fabricated into a shell around HD
  - Is a passive device
  - Can provide a uniform internal field
  - <Z> ≈ 7 (minimal dE/dx)



How would MgB_2 be used?
(Trapping a Transverse Field)

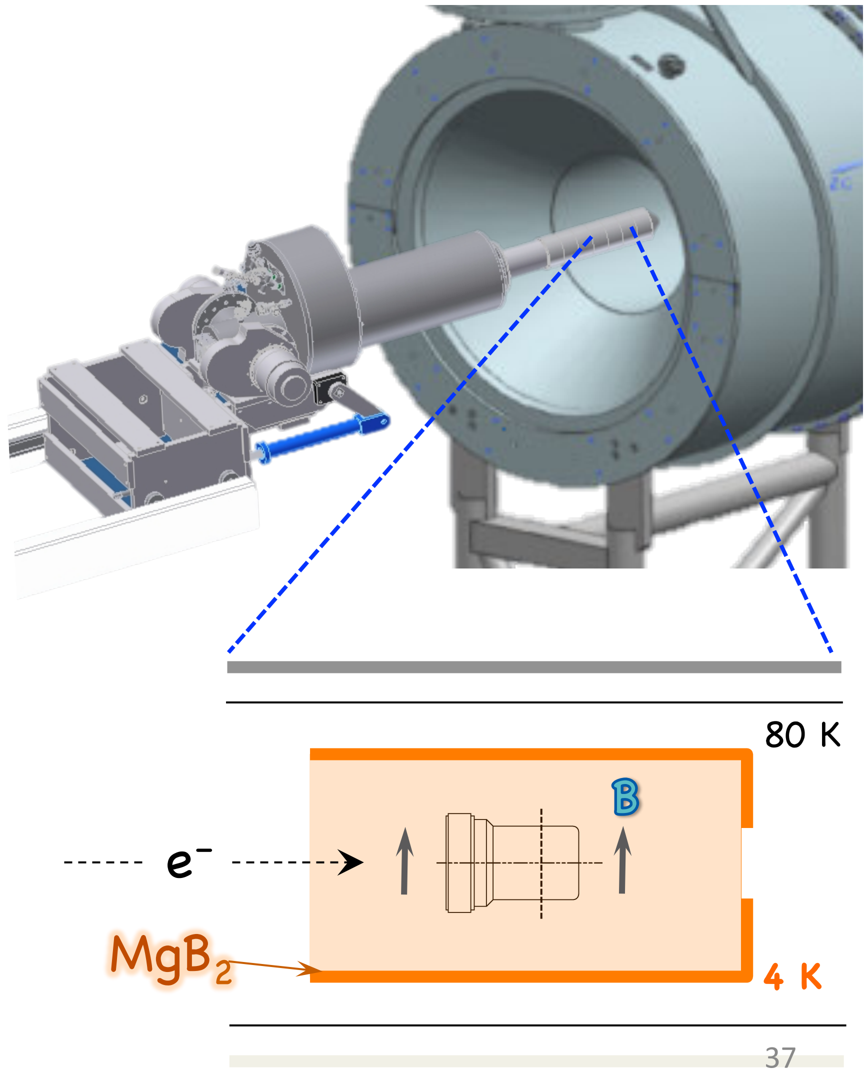
- Ramp up 1.25 T external magnet (transverse field) around nose of IBC
- Cool MgB_2 inside of IBC to 4 K (T_c = 39 K)
- Load polarized HD cell into IBC
- Lower external field
- The perfect diamagnetism of MgB_2 allows for the spontaneous generation of currents, maintaining the original internal field



How would MgB_2 be used?

(Cancelling the CLAS-12 Solenoid Field)

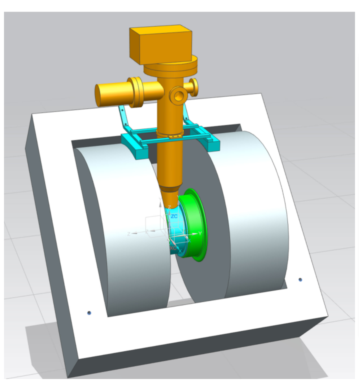
- IBC rotated into horizontal position and moved into CLAS-12
- CLAS-12 Solenoid ramped up
  ➔ currents again arise in MgB_2, maintaining original (transverse) field
- These complex currents can/will be much more intricate than could be achieved with an electromagnet



Summary of Prototype Tests in Ferrara

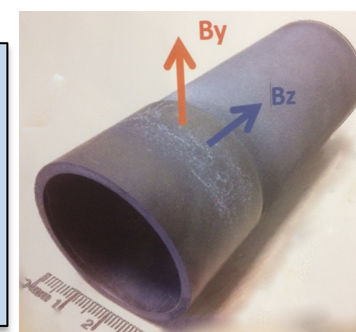
- Repeatable results indicate that MgB_2 shell can trap a transverse field of ≈1 Tesla.
- MgB_2 can maintain this internal field for weeks with negligible droop (0.0015 T over 1 month)
- MgB_2 shell can survive magnet quenches
  - Subjected to several quenches (flux jumps)
  - MgB_2 survived with no change in performance

Istituto Nazionale di Fisica Nucleare Sezione di Ferrara



MgB_2 shell held in 14 K cryocooler between poles of a 1 tesla dipole

MgB_2 prototype:
40 mm Ø
86 mm long
2 mm wall



Summary

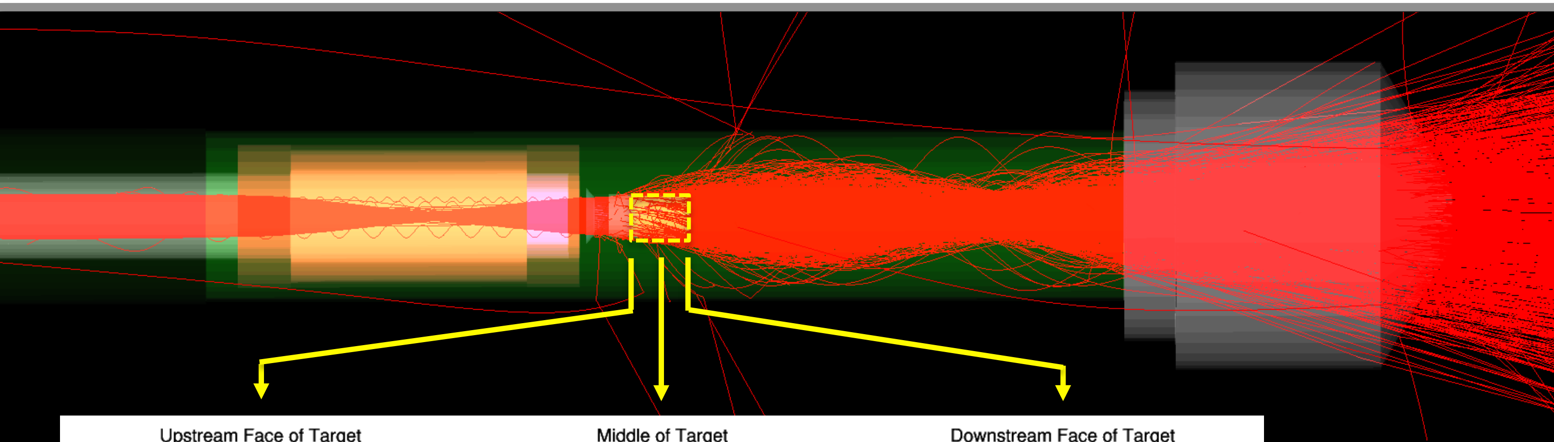
- HDice has been successfully used in the past with photon beams but its future lies in its use with electrons (eHD).
  - Three "high impact" proposals to use HDice with electrons in CLAS-12.
- Charged particle beams present a new challenge for HDice
  - Focus of current efforts
  - UITF eHD tests will allow for a study of the effects of an electron beam on the target as well as how to abate them.
- Cancelling the CLAS-12 Solenoid may be accomplished using a MgB_2 shell.
  - Second test of MgB_2 prototype: trapping a transverse dipole field <u>and</u> cancelling external solenoid field

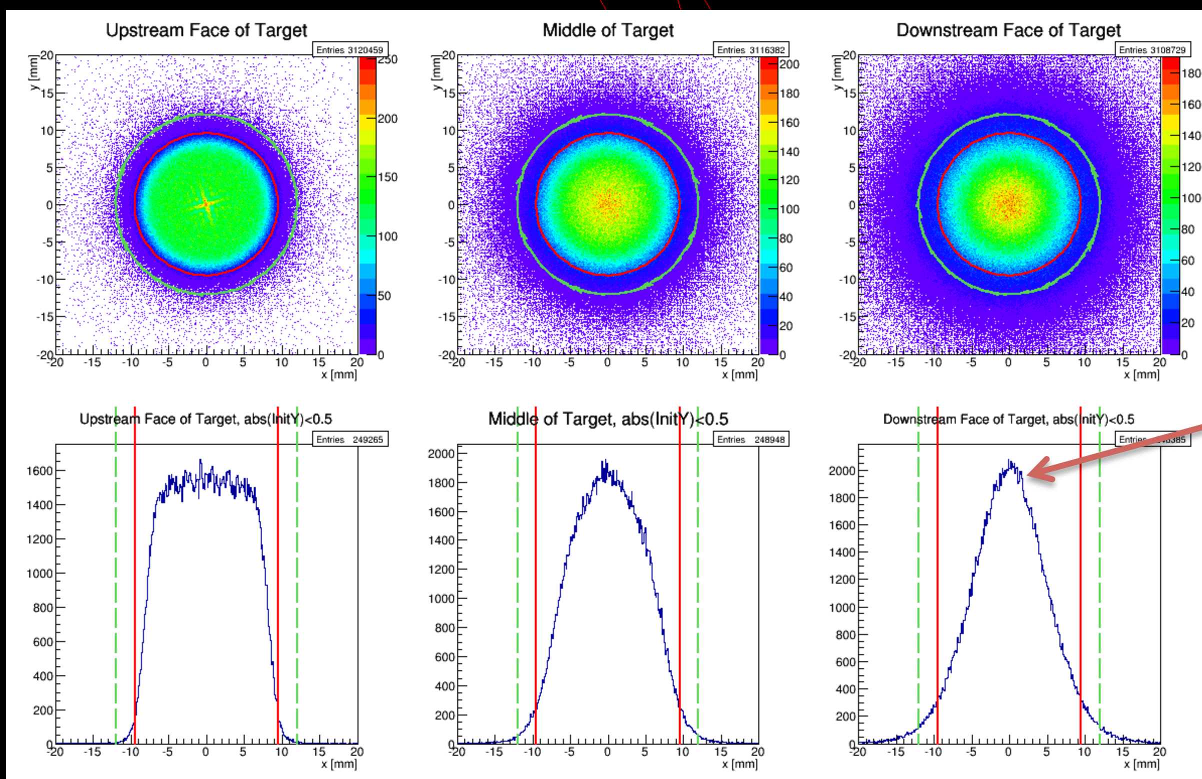
HDice

Jefferson Lab

END

Rastered beam profiles on 25 mm long target

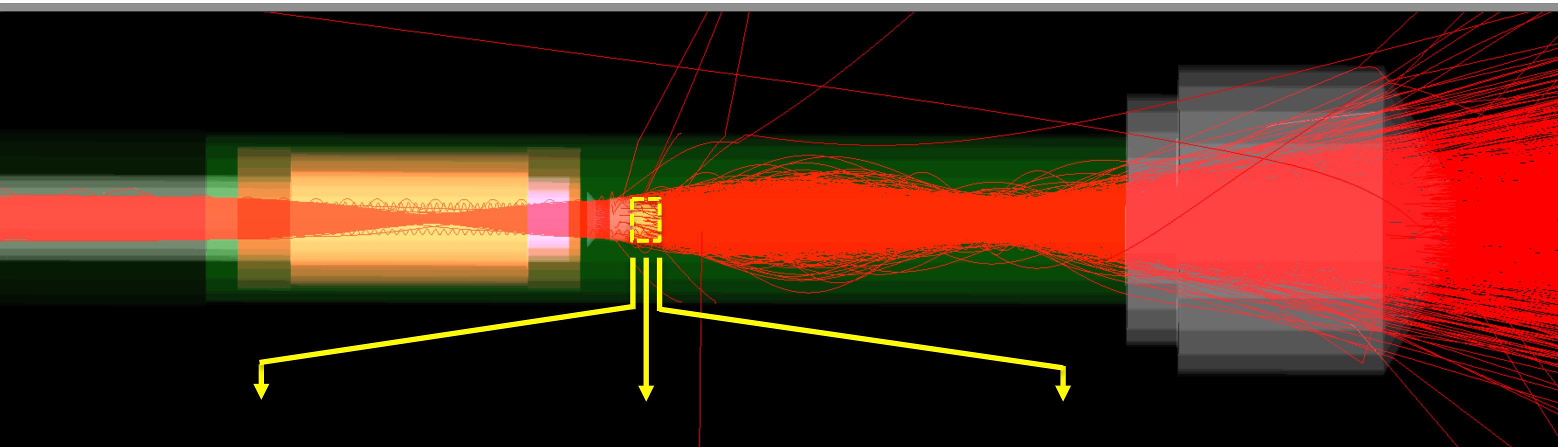


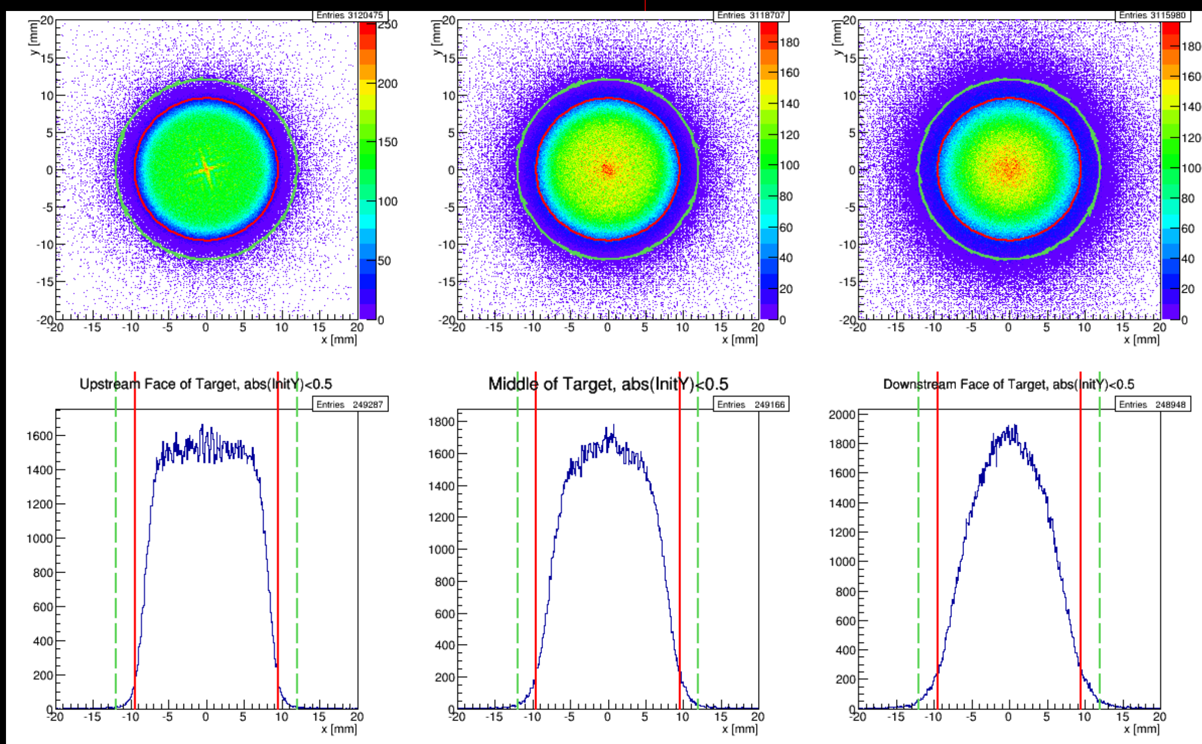


- back half of a 25 mm long target cannot be uniformly illuminated with beam, due to multiple scattering

⇔ concentrates heat and radiation damage

Rastered beam profiles on 12.5 mm long target





- compromise on ½ target length to distribute beam quasi-uniformly

⇔ *most of the 12.5 mm target length* can be filled with beam

HDice

eHD Luminosity

$\mathcal{L}$ [cm^{-2} s^{-1}] = dN/dt [s^{-1} in a perfect detector] • 1/σ_T [cm^{-2}]

= $(0.2 \times 10^{33}) \bullet T_{HD}(\mathrm{cm}) \bullet I_e(\mathrm{nA})$

for 2.5 cm long cell and I_e = 2 nA ➔ 10^{33}

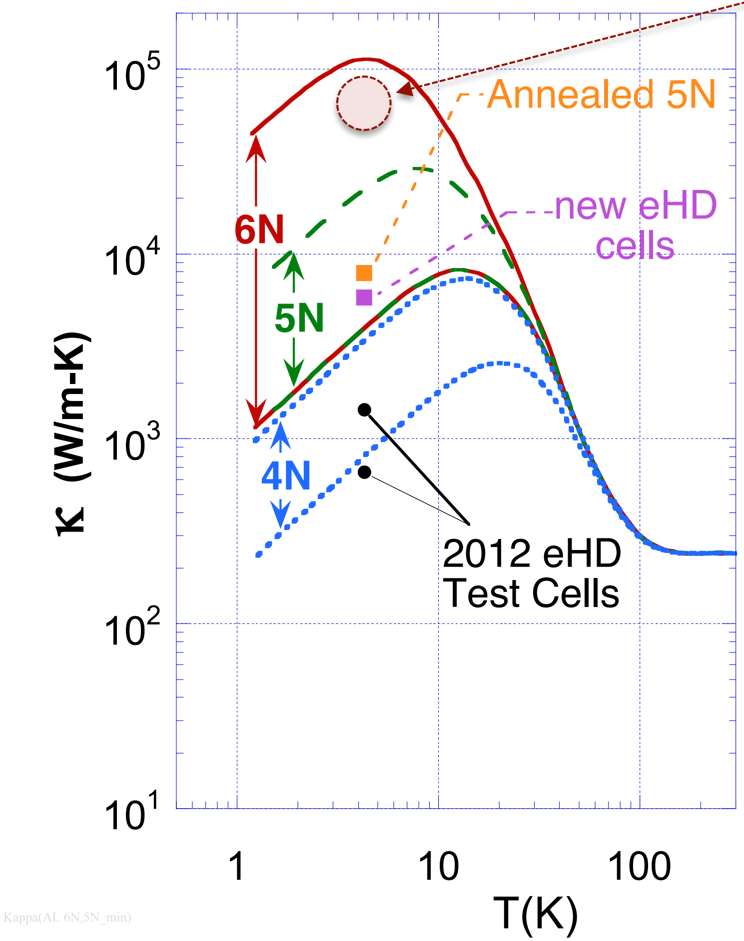
Room for future improvements in Al thermal conductivity

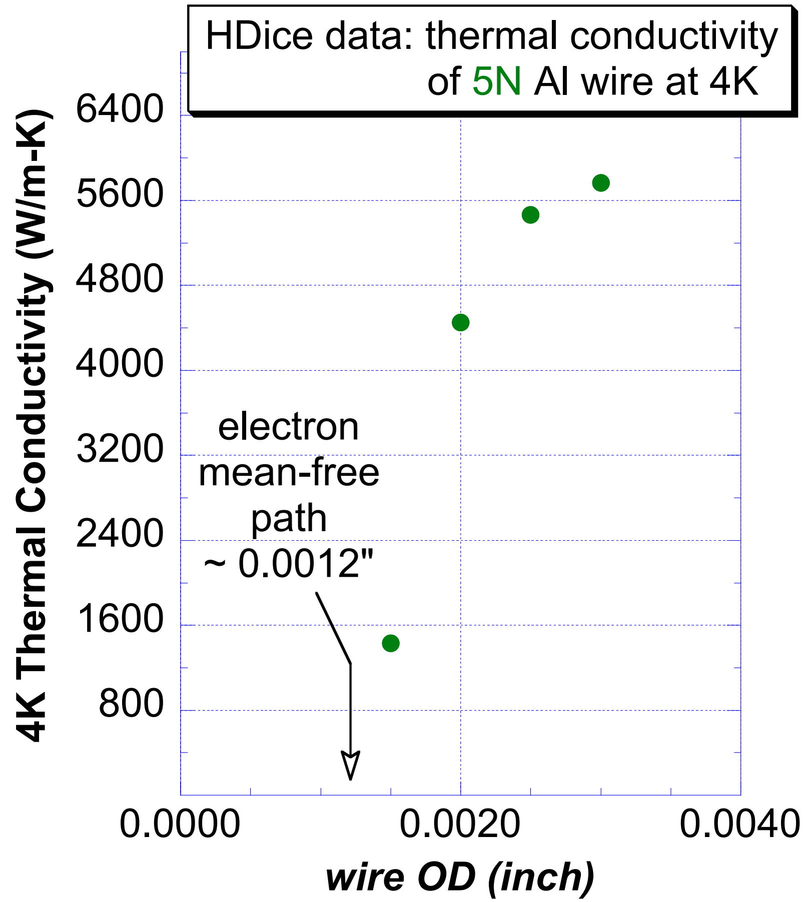
HDice data: (● ■ ■)

curves: —— 6N, —— 5N, —— 4N

Thermal Conductivities for pure Aluminum
A.L. Woodcraft, Cryogenics **45** (2005) 626

high 6N (99.9999%) Al wire could triple the target length

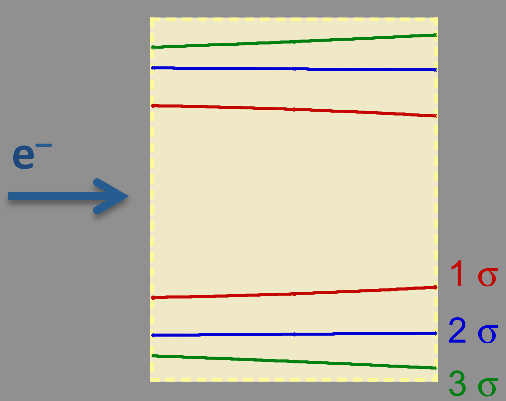




UITF vs Hall B

UITF

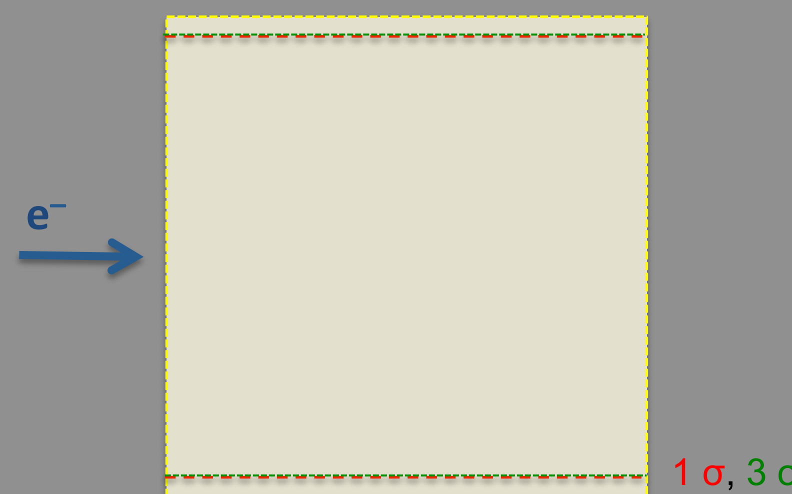
E_e = 7.86 MeV
Beam diameter = 17 mm, with tails
(*maximum size*)
HD diameter = 19 mm
(*1 mm clearance at 3 σ*)
HD length = 12.5 mm
(*max for quasi-uniform pwr*)



HD

Hall B

E_e = 10 GeV
Beam diameter = 23 mm, no tails
HD diameter = 25 mm
HD length = 25 mm



HD

UITF vs Hall B

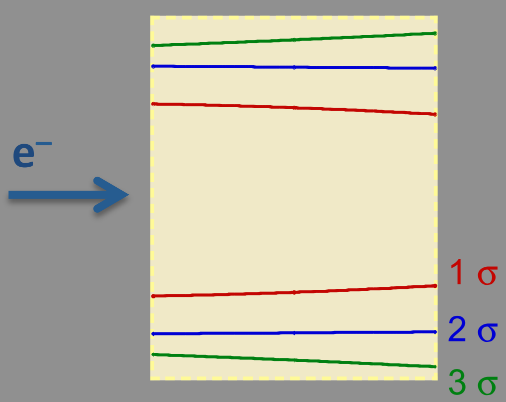
UITF

E_e = 7.86 MeV

Beam diameter = 17 mm, with tails

HD diameter = 19 mm

HD length = 12.5 mm



Power density at 1 nA

0.53 mW/cc (1 σ)

0.16 mW/cc (1 σ)

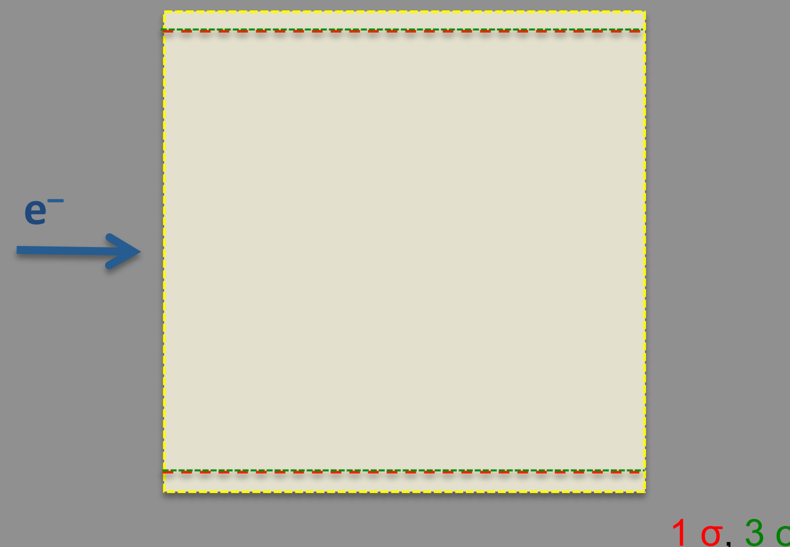
Hall B

E_e = 10 GeV

Beam diameter = 23 mm, no tails

HD diameter = 25 mm

HD length = 25 mm



Power density at 1 nA

0.13 mW/cc (1 σ, 1 σ)

UITF vs Hall B

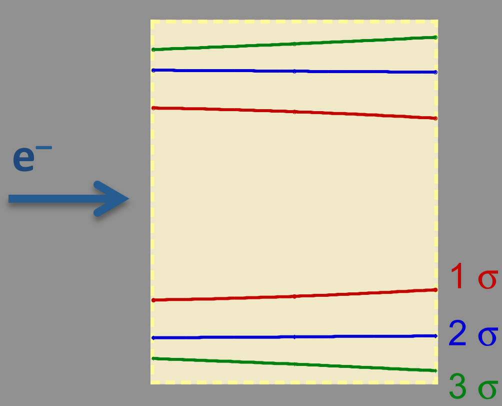
UITF

E_e = 7.86 MeV

Beam diameter = 17 mm, with tails

HD diameter = 19 mm

HD length = 12.5 mm



Power density at 1 nA

0.53 mW/cc (1 σ)

0.16 mW/cc (1 σ)

greater challenge! ⇔

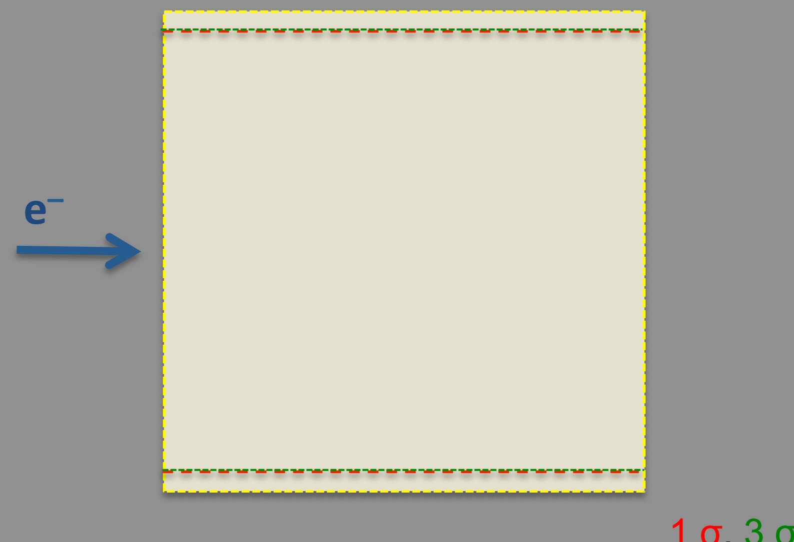
Hall B

E_e = 10 GeV

Beam diameter = 23 mm, no tails

HD diameter = 25 mm

HD length = 25 mm



Power density at 1 nA

0.13 mW/cc (1 σ, 1 σ)